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UNIVERSITY OF ALBERTA

THE REMOVAL OF AIRBORNE DUST FROM SWINE HOUSING BY ELECTROSTATIC PRECIPITATION

by

Susan Fournier

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A THESIS
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES AND RESEARCH
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE
OF MASTER OF SCIENCE

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EDMONTON, ALBERTA
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ABSTRACT

Airborne dust concentrations within swine confinement buildings can lead to health problems for stockpersons and animals as well as toward corrosion of barn fixtures and electrical equipment. Methods researched to reduce swine housing dust concentrations include: 1)Dispersion with air recirculation and ventilation; 2)controlling the source through feeding and management practices, and 3)using mechanical air cleaners. Due to the expense involved with increasing ventilation rates to control dust levels, an inexpensive, self-maintaining and efficient alternative is required. An electrostatic precipitator was developed to remove airborne swine dust from an environmental chamber. A split-plot factorial experimental design was used to test the effects of applied voltage and airspeed on the collection efficiency of the electrostatic precipitator.

The electrostatic precipitator was built into a recirculation duct in an environmental chamber at the Ellerslie Research Station, University of Alberta, Ellerslie, Alberta. The volume of the electrostatic precipitator was 0.13 m^3. The particle charging and collection mechanisms of the electrostatic precipitator included: 44 discharge wires and 12 grounded collection plates. The three applied voltage levels were: -10.3, -11.0 and -12.1 kVDC. The three airspeed levels were 0.55, 0.76 and 0.95 m/s.

The average particle concentration at the inlet to the precipitator was 41 particles/mL, with 1.9 μm as the mean diameter. The overall collection efficiency of the precipitator ranged from 18.5% at an applied voltage of -10.2 kVDC to 96.4% at an applied voltage of -12.0 kVDC. Applied voltage had a significant effect ($P<0.05$) on collection efficiency. Airspeed did not have a significant effect ($P<0.05$) on collection efficiency. When corrected for

different airflows and particle concentrations, the optimal airspeed was 0.76 m/s for all applied voltages.

The migration velocity of the dust toward the collection plates increased with applied voltage. Industrial design equations were used to determine the effect of different precipitator lengths and inter-electrode spacings on collection efficiency. Collection efficiency increased by approximately 5% when the precipitator length was increased by 50%. Inter-electrode spacing had little effect on collection efficiency. An applied voltage of -12.1 kVDC produced ozone levels of 0.21 ppm which exceeded the recommended TLV of 0.1 ppm.

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LIST OF SYMBOLS

Variable		Units
d_{NM}	- number median diameter,	μm
d_{MM}	- mass median diameter,	μm
d_{mean}	- mean diameter,	μm
n_d	- particle concentration for size range d,	particles/mL
N_t	- total particle concentration,	particles/mL
η	- collection efficiency,	%
η_d	- collection efficiency for size range d,	%
η_o	- overall collection efficiency,	%
E	- electric field,	$V \cdot m^{-1}$
I	- current density,	$A \cdot m^{-2}$
ρ	- resistivity,	$\Omega \cdot cm$
$\$$	- slip, fraction of dust uncollected,	
ϖ	- effective migration velocity,	$m \cdot s^{-1}$
A	- specific collection area,	$m^2 \cdot s \cdot m^{-3}$
L	- precipitator length,	m
v	- airspeed,	$m \cdot s^{-1}$
S	- inter-electrode spacing,	m
ϖ_k	- modified effective migration velocity,	$m \cdot s^{-1}$
η_k	- modified collection efficiency,	%

1. INTRODUCTION

The trend towards intensified swine production in confinement buildings has led to an increase in airborne contaminants and dust within the animal's and stockperson's environment. The characteristics of swine dust that may attribute to potential health hazards for humans or animals include: 1)Particle size in the respirable range; 2)high protein concentration; 3)high bacterial and fungal counts; 4)endotoxin activity, and 5)adsorbed irritating gases (Donham and Leininger, 1984).

The main constituents in airborne dust found in swine barns are feed and fecal particles and may also include other organic matter such as dander, urine, mold, pollen, insect parts and mineral ash (Donham and Leininger, 1984). The dust may also carry gram-negative bacteria, endotoxins, adsorbed ammonia (NH_3) and infectious agents (Donham and Leininger, 1984). The concentration of airborne dust particles is affected by many factors including animal activity, feeding methods, type and age of animal, natural versus mechanical ventilation, air humidity and barn cleanliness (Heber et al., 1988).

According to various surveys conducted in the United States, health complaints experienced by stockpersons working in swine barns included chronic bronchitis, sore throat, stuffy nose, sneezing, chest tightness, eye irritation, and shortness of breath (Heber et al., 1988). In swine, chronic coughing, lowered weight gains and increased incidences of enzootic pneumonia have been attributed to high levels of NH_3 and dust (Doig and Willoughby, 1971).

Research into mechanical dust removal methods for swine barns has included the use of filters, wet scrubbers, ionizers and electrostatic precipitators. Until now, a self-cleaning, inexpensive, safe and highly efficient air cleaning system has not been devised for use in swine barns. However, electrostatic precipitators are highly efficient at removing small dust particles such as the respirable particles found in swine housing air (Wark and Warner, 1981).

The purpose of this research was to determine the following: 1)The effect of applied voltage and 2)the effect of airspeed on the collection efficiency of an electrostatic precipitator using swine housing dust. An electrostatic precipitator specifically designed and fabricated in conjunction with a recirculation duct in an environmental chamber was used for this purpose. Industrial design equations were employed to predict the effects of voltage and airspeed on the effective migration velocity of the dust particles. The effect on collection efficiency was estimated for changes in precipitator length and inter-electrode spacing.

2. LITERATURE REVIEW

2.1 Terminologies in Dust Literature

2.1.1 Dust

The term dust is defined as "solid particles larger than colloidal size capable of temporary suspension in air" (Wark and Warner, 1981). Another definition used for dust is aerosol, a dispersion of microscopic solid or liquid particles in gaseous media. Dust within livestock housing is mainly of organic origin (Donham et al., 1986). Organic dust derived from vegetable matter includes livestock feed, grain, wood, cotton, pollen, molds, yeasts, bacteria and fungal spores. Organic dust derived from animal sources includes wool, hair, feathers, skin, dried manure, urine and gut epithelium (Lampman, 1982).

2.1.2 Nuisance Particles

There are generally two types of dust particulates: Fibrogenic and nuisance dusts. Fibrogenic dusts cause scar tissue in lungs when inhaled in excessive amounts. Nuisance dusts have a history of little adverse effect on lungs and do not produce significant organic disease or toxic effect when exposures are kept under reasonable control. The term "biologically inert" used to be applied to nuisance dusts. However, this is no longer applicable since there is no dust which does not invoke some cellular response in the lung when inhaled in sufficient amounts. Generally, the lung-tissue reaction caused by inhalation of nuisance dust has the following characteristics (ACGIH, 1985);

1. The architecture of the air spaces remains intact.
2. Collagen (scar tissue) is not formed to a significant extent.
3. The tissue reaction is potentially reversible.

2.1.3 Size

The size characterization for a dust particle is expressed as a micron (μm) or a micrometer. The diameter referred to in this thesis (unless otherwise specified) is the "aerodynamic size". The aerodynamic size is the diameter of a hypothetical sphere of unit density having the same terminal settling velocity as the particle of interest, regardless of its geometric size, shape and density (Honey and McQuitty, 1976).

2.2 Swine Housing Dust

2.2.1 Constituents

Through qualitative microscopic analysis, swine housing dust was determined to be heterogeneous and diverse in size, shape and composition (Donham et al., 1986). Several studies identified the components of airborne dust in swine housing as the following: 1)Feed (starch granules, grain meal, trichomes and corn silk); 2)swine fecal material (gut, microbial flora, gut epithelium and undigested feed); 3)swine protein (urine, dander and serum); 4)mold; 5)pollen; 6)grain mites, insect parts; 7) mineral ash; 8)gram-negative bacteria; 9)endotoxin; 10)adsorbed ammonia and 11)infectious agents (Donham et al., 1986; Stroik and Heber, 1986).

2.2.2 Microscopic Identification

Feed particles were determined to be the main component in swine housing dust through microscopic identification of starch particles and grain meal. Starch particles are of polygonal shape and birefringent with a maltese cross, generally within 15.3 and 21.6 μm (Stroik and Heber, 1986). Bran which is also an indication of feed particles is identified as being large, flat and nonbirefringent. The feed and fecal constituents of the dust both contribute to the 23 to 28.7 % protein content within swine housing dust. Skin particles are similar to the bran particles except that they tend to be flat and folded on the edges (Heber et al., 1986). Fecal material included particles within the respirable size range of 0.9 to 2.0 μm (Donham et al., 1986).

2.2.3 Potentially Harmful Components of Dust

The warm and humid environment present in swine confinement housing provides an excellent medium for proliferation of some other components of swine housing dust, such as fungi and bacteria (Merchant and Donham, 1989). The common fungi include species of *Pencillium, Fusarium, Aspergillus flavus, Scopolariopsis, Verticillium, Phycomycete* and *Paecilomyces* (Donham et al., 1986). As well both Gram-negative and Gram-positive bacteria are common and relatively high levels of endotoxin were found in swine confinement housing. Endotoxin levels average about 11 μg/g of dust (Donham, 1987).

These components can either be airborne themselves or be carried by dust particles. Dust particles are also capable of adsorbing irritating gases such as NH_3, which is often found to exceed recommended Threshold Limit Values (TLV), in swine confinement housing (Donham, 1987).

2.2.4 Mass concentration

Mass concentrations have varied with different studies. For pig finishing units using natural ventilation, the average total mass concentrations were: 9.6 mg/m^3 (Curtis et al., 1975b); 2.7 mg/m^3 (Meyer and Manbeck, 1986); 8.8 mg/m^3 (Heber et al., 1988); and 15.3 mg/m^3 (Donham et al., 1986). The average total mass concentrations for mechanically ventilated finishing barns were: 6.4 mg/m^3 (Curtis et al., 1975b); 15.3 mg/m^3 (Donham et al., 1986); 1.3 mg/m^3 (Meyer and Manbeck, 1986); and 6.9 mg/m^3 (Heber et al., 1988). The average total mass concentrations for mechanically ventilated farrowing rooms were: 1.4 mg/m^3 (Curtis et al., 1975b); 3.2 mg/m^3 (Donham et al., 1986); and 1.2 mg/m^3 (Meyer and Manbeck, 1986).

2.2.5 Number Density

Mass concentration indicates the total mass of dust per unit volume, rather than indicating the number of particles within a unit volume for a particular size range as given by number density. The average number density or particle concentration for mechanically ventilated finishing units and naturally ventilated finishing units were 9 particles/mL and 12.2 particles/mL, respectively (Heber et al., 1988). Other particle concentrations measured at the indoor temperatures of 21.9°C and 24.8°C were 2.3 and 1.4 particles/mL, respectively. The same study showed that for the different feeding methods of floor and feeder the particle concentrations were 2.4 and 1.3 particles/mL, respectively (Feddes et al., 1983) The lack of results based on number concentrations is due to the more general use of mass-based types of particle counters in the past.

2.2.6 Factors Affecting Dust Concentrations

The factors affecting dust concentrations, size and content include the type of ventilation, feeding methods, stocking density, age and type of animal, humidity, outside temperature, animal activity and barn hygiene. Owing to these factors as well as different methods of particle sampling and collection, the results vary between different studies. Naturally ventilated barns tend to have higher dust concentrations than mechanically ventilated barns at outside temperatures less than 21°C, due to lower ventilation rates and closed natural-ventilation openings (Heber et al., 1986).

Dust concentrations increase as the difference between inside and outside temperatures increases, as a result of lower ventilation rates required during cold weather conditions. An increased dust concentration was also found during nights as opposed to daytime, due to the decrease in outside temperature, and thus lower ventilation rates (Curtis et al., 1975a). As the inside relative humidity increased, the aerial dust concentration decreased due to an increased settling rate by particles which had adsorbed water vapour (Honey and McQuitty, 1976).

Restricted feeding versus ad lib feeding resulted in decreased dust concentrations, since feed particles are the main constituent in pig dust (Honey and McQuitty, 1976). Animal and stockperson activity also has an effect upon dust concentrations, with highest dust concentrations occurring during peak activity times. In one study, highest dust levels were encountered in a barn which had never been cleaned or washed whereas in the barn with the lowest dust concentrations, the floors were swept daily and the rooms were power-washed between each group of pigs (Heber et al., 1986).

2.2.7 Respirable Dust

The human respiratory tract and the location of particle deposition from 10 μm to less than 0.1 μm is depicted in Figure 2.1. The four main sections of the respiratory tract are: 1)Nose and throat; 2)trachea, primary; 3)secondary and terminal bronchi and 4)alveoli (Pedersen, 1990).

The particles that tend to deposit within the nose and throat area are between 5 and 10 μm. These particles can cause irritation to the throat, nasal passages and stomach, since particles inhaled through the mouth and swallowed, will be ingested. These particles may be cleared from these passages by mechanical means such as sneezing, nose blowing, rubbing and coughing (NRC, 1979). Concentrated buildup can occur on some of these surfaces which can exceed the rate of removal, resulting in long term deposition and possible irritation.

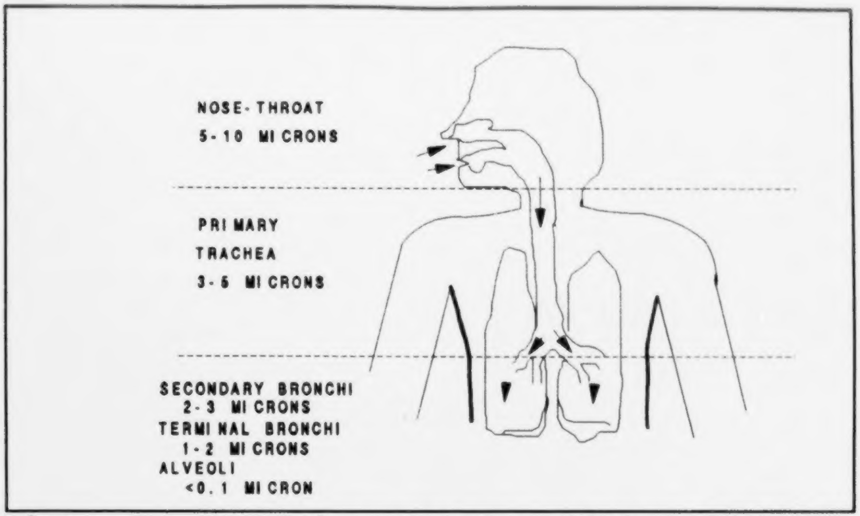
NOSE-THROAT
5-10 MICRONS
PRIMARY
TRACHEA
3-5 MICRONS
SECONDARY BRONCHI
2-3 MICRONS
TERMINAL BRONCHI
1-2 MICRONS
ALVEOLI
<0.1 MICRON

Figure 2.1 Deposition of dust particles within the human respiratory tract. Adapted from Pedersen (1990).

The particles that deposit within the primary trachea are generally between 3 and 5 μm. Insoluble particles that have deposited in the mucus lining of the trachea are generally transported back up to the nose and throat area, along with the mucus by cilia movement, within a day. Soluble particles however are cleared faster through absorption into the bronchial blood flow.

Particles between 2 and 3 μm deposit within the secondary bronchi, which extend off the trachea, before splitting into the terminal bronchi, where particles between 1 and 2 μm deposit. The particles clear as in the trachea, by transportation in the mucus or through absorption in the bronchial blood flow. As the bronchial branching increases, the air speed decreases, approaching the settling velocity of particles of this size, increasing the rate of deposition within this area.

Particles that pass through the terminal bronchi enter the alveoli, and are generally less than 0.1 μm. Beyond the ciliated airways, gas exchange occurs in the alveoli. The epithelium is very thin, permitting soluble particles to enter the pulmonary blood within minutes. Insoluble particles deposited in this zone are removed very slowly with clearance half-times measured in days, months or years (NRC, 1979).

2.2.8 Frequency of Respirable Particles

From Danish investigations for swine housing, the frequencies of airborne dust particles within the size ranges of 0.5 to 1.5 μm, 1.5 to 3 μm and 0.5 to 5 μm is 22%, 28% and 70%, respectively (Pedersen, 1990). In a study of 11 swine finishing units in Kansas, respirable fractions by number ranged from 83 to 98% over the particle size range of 1.8 to 6.9 μm (Heber et al., 1986). In another study, results showed that 95% of the dust in swine buildings are considered to be within the size damaging to lungs (Bundy and Hazen, 1973).

From samples collected from eight commercial hog farms, the average respirable dust percentages for farrowing, nursery and breeding rooms were 63%, 19.6%, and 46.8%, respectively (Meyer and Manbeck, 1986). Generally, farrowing rooms had less total mass concentrations, than did the finishing rooms, however the incidence of respirable particles was greater in the farrowing rooms (Heber et al., 1987).

2.2.9 Deposition of Dust Particles

Since feed particles are generally larger than 5 μm they would deposit in the nose and throat area. The fecal particles being much smaller in size, generally less than 3 μm, would deposit within the bronchi and alveoli, carrying other irritating agents such as ammonia, bacteria and endotoxins to the lungs.

2.2.10 Health Hazards for Humans

The effects of airborne dust on stockpersons is usually determined from surveys which include information on their varying backgrounds, working conditions and duration of exposure. Since full-scale confinement buildings have only come into existence since the 1960's, people have only recently worked in such an environment for a lifetime. Therefore the relationship between exposure to swine housing dust and long-term respiratory illness has not been firmly established.

The symptoms experienced by swine confinement workers and their respective prevalence among the workers are: cough, 67%; sputum or phlegm, 56%; scratchy throat 54%; runny nose 45%; burning or watering eyes, 39%; headaches, 37%; tightness of chest, 36%; shortness of breath, 30%; wheezing, 27%; and muscle aches and pain, 25% (Donham, 1987). In another study, similar symptoms were experienced and the majority of symptoms were noticed within thirty minutes after entering the confinement unit. Most of the symptoms disappeared within 1 to 12 hours after leaving the confinement unit (Heber et al., 1988).

The clinical conditions that seem to be present among people working in swine confinement buildings include:

1) Acute or subacute syndromes
    A. Sudden collapse — Exposure to high
        Respiratory distress → levels of H_2S
        Pulmonary edema — from manure pits
    B. Asthma-like syndrome → 10 to 12%
    C. Acute-subacute bronchitis → 70 to 90%
2) Delayed Syndrome
    A. Organic dust toxic syndrome → 10 to 15%
3) Chronic syndromes
    A. Chronic bronchitis → 55%

B. Obstructive symptoms	→ 38%
Hyperactive airways	
C. Other chronic diseases	
Chronic obstructive pulmonary disease	unknown
emphysema	unknown

The above information was based upon the accumulation of case records, the interpretation of symptoms, and the history and course of the illness (Donham, 1987). Smokers experienced a greater prevalence and severity of chronic bronchitis than did nonsmokers.

Organic dust toxic syndrome (ODTS) was generally experienced 4 to 6 hours after working for several hours in a confinement house especially during high activity operations such as handling, moving or sorting animals (Donham, 1987). The symptoms of ODTS include fever, malaise, muscle aches and pains, headache, cough and tightness of chest. This syndrome may be caused by inhaled endotoxins from aerosolized gram-negative bacteria and sensitization to proteinaceous materials (Rylander et al., 1986).

2.2.11 Health Hazards for Animals

The deposition of dust particles within the respiratory tract of swine is similar to that in humans. However since the animal's respiratory tract is generally at a lower height in relation to a human's, there would be more incidence of larger dust particles accumulating within the animal's upper respiratory tract. The fact that a 25% improvement in growth rates when air was filtered to remove dust, indicates that dust levels do affect weight gains (Carpenter, 1982). In another study, no significant effect on growth rates on pigs from 1 to 7 weeks of age was noticed (Doig and Willoughby, 1971). A beneficial effect of filtering was noticed on mature animals since young growing animals and humans have a higher tolerance to infection than do mature animals and humans.

In most studies however, histological changes did occur in the upper respiratory tract. An increase in the thickness of the tracheal epithelium and a decrease in the number of tracheal epithelial goblet cells was evidenced in young pigs exposed to dust and ammonia for up to 6 weeks (Doig and Willoughby, 1971). One study demonstrated that there was a significant correlation between the number of particles in the range of 10 to >15 μm, counts of bacteria, total dust, and gravimetric dust concentrations in a farrowing house and an increased severity of conchal atrophy (a symptom of atrophic rhinitis) at slaughter (Smith, 1987).

The endotoxins from the viable and non-viable bacteria transported by the dust particles act as a physical burden to the mucociliary system and as a challenge to the immune system. The dust and the bacterial particles in the dust may facilitate the entry of pathogens (Smith, 1987). Particles of protein are antigenic, and due to the 23 to 28.7% protein content present in airborne dust act as a substantial challenge to the local immune system in the respiratory tract.

2.2.12 Acceptable Dust Levels

The American Conference of Governmental Industrial Hygienists (ACIGH) has established threshold limit values (TLV's) for nuisance dusts and other substances. The TLV's represent maximum acceptable concentrations of substances under which all workers may be repeatedly exposed day after day without adverse effects (ACGIH, 1985).

The recommended TLV's for nuisance particulates are 5 mg/m^3 and 10 mg/m^3, for respirable and total particles, respectively. In this case respirable mass represents 50% of the total mass. Assuming the density of the particles is 1

g/cm^3, and the average particle sizes of respirable dust and total dust are 2.5 μm and 5.0 μm, respectively; the resulting TLV's based on particle count are 611 particles/mL and 153 particles/mL, for respirable and total dust particles, respectively.

The mass based TLV's were determined to be unreasonable for swine housing environments, due to symptoms of health effects experienced by the stockpersons at these levels. As well the equivalent particle number densities are much higher than the particle concentrations at which adverse effects are experienced by workers and animals. Through studies to determine the maximum level before health symptoms have been experienced by stockpersons, Donham has recommended TLV's appropriate for swine confinement houses.

Table 2.1 Recommended exposure thresholds in swine buildings (Donham, 1987).

Total dust, mg/m^3	2.4
Respirable dust, part./mL	37
Respirable dust, mg/m^3	0.23
Endotoxin $\mu g/m^3$	0.08
Carbon dioxide, %	0.154
Total microbes, cfu[1]	$4.3x10^5$
Bacteria cfu x $10^6/m^3$	$6.3x10^5$
Molds, cfu/m^3	$1.3x10^4$
Respirable microbes, $count/m^3$	$2.4x10^7$

1 - colony forming unit

The recommended levels of various contaminants are given in Table 2.1 and include total dust concentrations of 2.4 mg/m^3, and respirable dust concentrations of 0.23 mg/m^3, approximately 76% and 95% less than the respective TLV's established for nuisance dusts by ACGIH (1985).

2.3 Methods of Dust Collection

In swine confinement housing three general methods by which airborne dust concentrations can be reduced are: 1) Dispersion of dust; 2) controlling the source and 3)mechanical removal of the dust particles from the air.

2.3.1 Dispersion

Dispersion contributes to reducing concentrations near a source but does little to reduce overall dust concentrations. Dispersion can be achieved by a recirculation fan and duct that provides good mixing of the air within a barn. When combined with the ventilation system further dispersion of aerial dust occurs through dilution with incoming fresh air. Ventilation systems are generally not designed specifically as a dust removal system, since high ventilation rates would result in high supplemental heating costs during cold weather conditions.

Ventilation rates are established to remove the heat, moisture and gases produced by the animals. The two design ventilation rates established for confined livestock buildings are the minimum (winter) and the maximum (summer) rates (Agriculture Canada, 1988). The required ventilation rates for swine depend upon the following factors: 1)Type of animal (dry sow, farrowing sow and litter, weanling pig, grower or finisher) to be housed; 2)the type of housing (group versus individual pens, partially versus fully slatted flooring or all-in/all-out versus continuous housing); 3) the stocking density and 4)the type of manure system (Agriculture Canada, 1988).

The success of these design ventilation rates to provide proper moisture and heat balances can be affected by specific housing and management practices. Similarly, the ventilation system can only remove a fraction of airborne contaminants such as dust, especially under cold weather conditions when the exhaust fans are operating at the recommended minimum. Therefore the control of dust by some other method appears to be desirable.

2.3.2 Controlling the Source

Several production and management practices can be used to reduce the production of dust particles. Since feed is the main component of pig dust, methods to reduce feed wastage should be employed, such as restricted instead of ad lib feeding, closed feed delivery systems including conveyors, and covered feeder hopper openings. Also, the addition of edible oils to the feed can reduce airborne dust concentrations (Gore et al., 1986; Welford et al., 1990).

Fecal particles, which can be a major component of respirable dust can be controlled by proper animal dunging habits including dunging in the proper area of the pen. If recommended stocking densities are exceeded, high amounts of feces and activity within a pen could result. The dried residue of any feces on the pen floor could be pulverized by the activity into small particles and be entrained into the airspace. If the room temperature exceeds that recommended, animals may wallow in the feces to cool off thus further spreading the feces throughout the pen. Improper direction of incoming air jets may affect the animal's dunging behavior by either causing an area to be drafty or too warm. Since dunging usually occurs within the pen where the environmental conditions are most undesirable, this must coincide with the slatted area in the rear of the pen.

Sweeping the pens and alleys on a daily basis can reduce the accumulation of wasted feed, feces, hair and other animal products. Hosing down the pens regularly is not always possible especially in a continuous production system. Batch rearing systems enable a period in which rooms are empty of all animals and can be cleaned with a pressure washer. This is recommended not only to clean the pens of all remaining particulates but also to remove any insects and infectious agents which could be transferred from one group of animals to another.

2.3.3 Mechanical Dust Removal

Mechanical dust removal methods researched for swine housing include: 1)Fabric filters, 2)wet scrubbers, 3)ionization and 4)electrostatic precipitation (Carpenter, 1987). These cleaners are generally much smaller, more affordable and adaptable to swine housing as compared to their larger and more expensive industrial counterparts.

2.3.3.1 Filters

There are two applications for air filtration in swine housing units: 1)at air intakes and exhausts; or 2)within the animal house (Carpenter, 1987). The first type is generally used for rooms containing laboratory animals especially where pathogens are involved. The implementation of filters at air intakes and exhausts can be applied to swine housing to reduce external pollution from particles and odors and the chance of spreading infectious diseases to other buildings. This is generally not a feasible system, however since the filters would have to be cleaned or replaced often to maintain optimum airflows through air intakes and exhaust openings (Carpenter, 1987).

The majority of dust particles identified in swine houses are generated from within the building by its inhabitants

(Heber et al., 1986). The use of internal air filters in conjunction with a pre-existing recirculation system can decrease concentrations within the building. If there is no existing recirculation system the fabric filter can be placed within a duct in series with a fan within the room.

The British National Institute of Agricultural Engineering (NIAE) developed an experimental filter unit independent of the ventilation system. The unit consisted of a suction box to which the filter material was attached. The dust collected upon the filter surface and was removed by vacuuming the surface. Experiments performed with early-weaned pigs in a rhinitis-infected herd resulted in a 25% greater growth rate between 3 and 7 weeks of age (Carpenter, 1984). There was also a significant improvement in number of days to slaughter in the later fattening stage of early-weaned pigs. The effects of this system depend upon the health status of the herd. Those with respiratory diseases were more likely to benefit from air filtration.

In another experiment, a filter material which was specified at removing particles > 5 μm was actually effective at removing a proportion of the particles smaller than 5 μm, as well as the particles greater than this size (Carpenter et al., 1986). This was probably due to the improvement in efficiency of fibrous filters that can occur due to the filtering effect of the particles already collected upon the filter surface. However, as the filter continues to accumulate dust particles upon its surface the pressure drop across the layer increases so that the system fails to operate efficiently. Filters must be either cleaned or changed regularly thus resulting in high maintenance costs. The initial costs are generally low compared to other systems, however the cost of regular replacement must be considered.

2.3.3.2 Wet Scrubbers

Wet scrubbers collect particles from over 100 μm to 2 μm by impact between particles and wetted surfaces or water droplets. The system generally includes a spray tower in which water falls in droplets though a packing material, in the opposite direction to the flow of the dust-laden air. The particles that actually impact with water droplets adsorb the water onto their surfaces increasing their density and are washed out with the rest of the water droplets.

The advantages of using a wet scrubber in swine housing are as follows: 1)Removal of ammonia and carbon dioxide as well as dust and microbes; 2)self cleaning, therefore low maintenance; 3)facility for addition of disinfectant for better anti-microbial effects; 4) humidification of dry air, as sometimes found in flat deck weaner houses; 5)use as dehumidification if cold water is used and 6)can be used for summer cooling thus reducing maximum ventilation rates required (Pearson, 1988). Disadvantages of using a wet scrubber in swine housing are as follows: 1)High capital cost; 2)high running cost, due to water consumption, which can be reduced if the water is recycled; 3)large size of the unit may not fit into some buildings and 4)the humidification effect may not be desirable (Pearson, 1988).

An experiment performed with wet scrubbers resulted in removal of 90% of particles > 5μm, 50% of particles > 1μm and 21% of the total ammonia measured (Licht and Miner, 1979). Another design removed 40% of particles, 25% of ammonia, 15% of carbon dioxide and 50% of micro-organisms (Pearson, 1986).

2.3.3.3 Ionizers

Ionizers are similar to electrostatic precipitators, except that ionizers include only a particle charging mechanism whereas an electrostatic precipitator includes a particle charging and collection mechanism. A high voltage power supply attached to discharge wires supplies the electric field to ionize the air molecules surrounding the discharge wires into positive and negative ions. If the wire is negatively charged with respect to ground, the electrons and negative ions released by the ionization are repelled from the wire at high accelerations. Conversely the positive ions are attracted to the discharge wire. If the wire is charged positively (with respect to ground), the positive ions are repelled at high speeds and the negative ions and electrons are attracted to the discharge wire.

As the dust particles collide with the released ions (negative or positive) they become charged and plate out upon the nearest grounded surface or surfaces charged oppositely to the discharge wires: such as pen enclosures, fans, light fixtures, environmental controls, pipes, conduit and walls. The plating effect upon the room surfaces may result in corrosion of these surfaces as well as the possibility of electrical fires especially after washing has been performed and the dust around electrical controls is moist (Nabben, 1973). Since the dust is not actually removed from the room, it can be re-entrained into the airstream through air movements created by stockpersons or the animals as well as the normal airflows caused by the ventilation and recirculation systems.

One experiment performed in environmental and animal chambers, was used to determine the effectiveness of ionization as a dust control measure (Bundy, 1974). Within the animal chamber the air was ionized by using negatively charged needle points located 1.2 m above the floor of the pens. The needle points were located in a rectangular grid pattern over the pens and charged with approximately -12 kVDC, with a current rating of 0.05 mA. An aluminum collector plate

4.3 m long and 0.8 m high was located in the exhaust end of the building. This collector plate was charged with approximately +8 kVDC, with a current rating of 0.05 mA (Bundy, 1974).

Of the airborne dust present in this experiment, 50% of all particles by number were within the size range of 0.5 μm to 1.0 μm. Ionization was relatively more effective under zero ventilation than with ventilation. Ionization also increased the dust decay rate when used in conjunction with ventilation fans. The deposition of dust upon the ceiling, sidewalls and exhaust-fan motors and controls was higher when ionization was used. The charged dust particles did deposit upon the oppositely charged collector plate. It was finally concluded that for ionization to be an effective method of dust control in the animal environment, the ceiling and sidewalls should be charged similarly to the particles so as to direct the particles to a specific collection surface, that can be periodically cleaned (Bundy, 1974).

The second part of this investigation included testing a similar system without animals to determine the effect of humidity on dust decay rates with varying recirculation rates and ionization. Two discharge electrodes were located 0.25 m above the floor and 0.46 m from each of the sidewalls, within a modified plant growth chamber. The applied voltage on the discharge wires was -12 kVDC. An aluminum collector plate 0.8 m by 1.4 m charged with +8 kVDC was located opposite to the air duct to provide sufficient air flow across its surface. A dusty atmosphere was produced in the environmental chamber using ground feed (14% protein, corn-bean meal ration for finishing pigs) that was dropped onto the floor from a container at a distance of 1 m above the floor.

The conclusions from this section included: 1) Dust removal by air ionization is not affected by humidity and 2) the air movement across a collector plate affects the collection efficiency of the ionization collection system (Bundy, 1974).

Another experiment was conducted to determine the following: 1) The total bacteria decay utilizing ionized air; 2) to measure the decay of aerosols by utilizing ionized air and 3) to compare two methods of ionization for the control of aerosols (Bundy and Veenhuizen, 1987).

One system included charging 6 needles suspended 0.15 m below the ceiling, with -22 kVDC while the ceiling and sidewalls were charged with -15 kVDC and +10 kVDC, respectively. The ceiling was negatively charged to drive the electrons formed by the corona around the wires toward the aerosol and to attract the positive ions. When compared to the decay rate of the dust particles without ionization, ionization produced a significant reduction in the number of dust particles greater than 0.5 μm, within 30 minutes (Bundy and Veenhuizen, 1987).

The second system in this experiment included releasing negative ions from an electron generation and air distribution system. The electron generation procedure included passing air through a special chamber in which 65 needle points were charged with -28 kVDC potential. The air entered the animal chamber through a distribution duct which was lined with an electrical conducting material that was charged with -10 kVDC. The chamber which enclosed the charged needles was also lined with this material and charged with -10 kVDC to capture the positive ions to avoid recombination of the electrons and positive ions before charging of the particles could occur.

This system provided a greater decay rate in the number of dust particles greater than 0.5 μm within a 30-min period as compared to using no ionization. However, this sytem did not have as great a decay rate as the previous system which employed generating the ions directly within the animal chamber (Bundy and Veenhuizen, 1987).

2.3.3.4 Electrostatic Precipitators

Some of the ionizers discussed in the previous section included a collection plate, however these plates were not considered the main dust collector, since the dust tended to plate out on many surfaces. Within an electrostatic precipitation system a particle charging and particle collection mechanism are combined to form a completely contained system. Commercially-available precipitators designed for residential furnaces have not been tested in swine housing.

In an experiment performed for broiler chicken housing, an electrostatic precipitator was placed in series with a coarse and fine filter. The Honeywell electrostatic precipitator (Model F50A 1058-1) had a rated dust collection efficiency of 99%, with a pressure loss of 0.5 Pa. The electrostatic precipitator removed up to 52% of the total dust mass in the air that had passed through the fine filter giving a combined removal efficiency of 98% (Williams, 1989). The performance of the electrostatic precipitator changed from week 1 to week 2, since half of the elements had short-circuited, reducing the collection efficiency.

In a preliminary investigation towards this thesis research the collection efficiency of a residential type two-phase electrostatic precipitator was tested for different organic dusts including: flour, icing sugar, corn starch, milk powder and swine housing dust (Fournier and Feddes, 1991). A volume of 5 mL of each dust was dropped through an area of

0.025 m by 0.06 m of an Electroair (Model Sas-10) Electrostatic Precipitator. The operating voltage of the precipitator was +6.2 kVDC. The results were based upon the mass collection efficiency, which represents the ratio between the mass of the 5 mL volume sample that was collected by the precipitator and the total mass of the 5 mL volume dust sample.

The rated efficiency for this precipitator was 99%. The collection efficiencies of the electrostatic precipitator were 92.5%, 23.9%, 71.0%, 45.7% amd 67.3% for flour, icing sugar, corn starch, milk powder and swine housing dust, respectively. The particles within the size range of 0.5 μm to 1 μm were collected with less efficiency than those particles greater than 1 μm, for each of the dusts. For swine housing dust, 59.4% by number of the original dust sample was within the size range of 0.5 to 1 μm whereas 61.1% by number of the uncollected dust was within this size range (Fournier and Feddes, 1991).

Extending the research performed on the use of ionization in swine housing, three experimental systems employing electrostatic precipitation were developed (Veenhuizen and Bundy, 1990). The first system included dust collectors located between ionizing electrodes. The 4 discharge electrodes were charged with -24 kVDC and enclosed by rectangular plastic mesh boxes. The collection mechanism included 9 long, coated, aluminum tube collectors that were charged with +16 kVDC. It was expected that, as dust particles passed by the discharge, electrodes they would be bombarded with negative ions, and thus become negatively charged. As these charged particles would flow through the collector tubes, due to airflows within the building, the positive charge on the walls of the tube would cause the particles to deposit upon their surface.

The second system included the use of 10 ionizing wires charged with -24 kVDC within cylindrical mesh enclosures. The collection mechanism consisted of 5 semi-circular trough-plate collectors. The collector plates which were charged with +16 kVDC, were placed 0.61 m below the ionizing wires. The ionizing wires were placed length-wise with respect to the animal pens. The third system was similar to the second system, except the configuration of the ionizing wires was along the width of the animal pens.

The percent reductions based on particle counts, in dust levels for systems 1, 2 and 3 were: 48.6%, 52.8% and 53.7%, respectively (Veenhuizen and Bundy, 1990). For the particle size ranges of 0.5 to 1 μm, 1 to 2 μm and 2 to 5 μm for system 3, the percent reductions were 42.6%, 48.3% and 58.9%, respectively. It was concluded that air movement patterns across the collector surface and ionizing electrode affects the collection efficiency of the ionization system. The configuration of the collection plates with respect to the discharge electrodes and the airflow in the chamber affected the collection ability of each of the three systems. No significant dust accumulations occurred upon ceilings, walls, pen enclosures, fans and controls due to the close proximity of the collectors to the ionizers.

2.4 Aerodynamic Behavior of Dust Particles

A particulate sample can be described using three diameters: the modal, median and mean diameters. The modal diameter is the diameter at which the greatest number of particles occur. The number median diameter, d_{NM} is the diameter for which 50% of the particles are larger (smaller) than d_{NM} by count. The mass (volume) median diameter, d_{MM}, is the diameter for which the mass of all particles larger than d_{MM} constitutes 50% of the total mass. The third diameter is the arithmetic mean diameter, d_{mean} (Wark and Warner, 1981).

Figure 2.2 represents a hypothetical size distribution of a particulate sample, which is based on a continuously distributed system. The values of $n(d_p)/N$ represent the ratio of the number of particles within the size range of d_p to the total number of particles within the entire sample. The curve $N(d_p)/N$ represents the ratio of the cumulative number of particles less than a particular size to the total number of particles within the entire sample. The diameter at which the curve of $n(d_p)/N$ intersects the curve of $N(d_p)/N$ for a particular sample is the arithmetic mean diameter (Wark and Warner, 1981). The left scale of Figure 2.2 representing $n(d_p)/N$ extends from zero to the maximum value of $n(d_p)/N$. The right scale on the other hand must always range from 0 to 1.0 since $N(d_p)/N$ represents an accumulation of all particles in a sample.

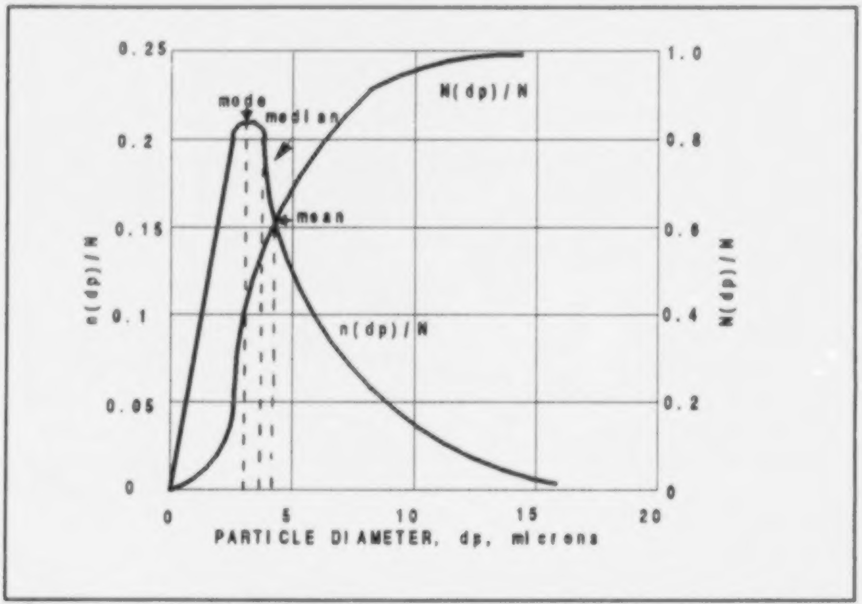

Figure 2.2 Hypothetical size distribution of a particulate sample. Adapted from Wark and Warner, (1981).

Realizing that particles of different sizes settle and behave differently while suspended in air will enable an understanding of the physical behavior during dust collection. Particles less than 0.1 μm in size, display a behavior similar to that of molecules and display large random motions caused by collisions with gas molecules as in "Brownian motion" (Lampman, 1974).

Particles between 0.1 and 1 μm tend to follow the aerodynamic flow of the gas in which they are suspended according to "Stoke's Law" (Lampman, 1974). A correction for slip, "Cunningham's Factor" is added to the general Stoke's equation for these particles. Particles larger than 1 μm but smaller than 20 μm tend to follow the motion of the gas in which they are suspended according to "Stokes Law" (Lampman, 1974). The particles larger than 20 μm have high settling velocities and, therefore, remain airborne for shorter periods than smaller sized particles. The Stoke's diameter is similar to the aerodynamic diameter except that the density is assumed to be the same as the parent material of the dust particle instead of 1 g/cm^3.

A particle's settling velocity is defined as the constant downward speed that a particle attains in a direction parallel to the earth's gravity field as it overcomes the forces due to buoyancy and frictional drag. Typical settling velocities for particles of 1 g/cm^3 density are (Wark and Warner, 1981):

0.1 μm	4×10^{-4} mm/s
1 μm	4×10^{-2} mm/s
10 μm	3.0 mm/s
100 μm	300 mm/s

Figure 2.3 illustrates the recommended air cleaner as well as technical definitions for the various size ranges of particles (Wark and Warner, 1981).

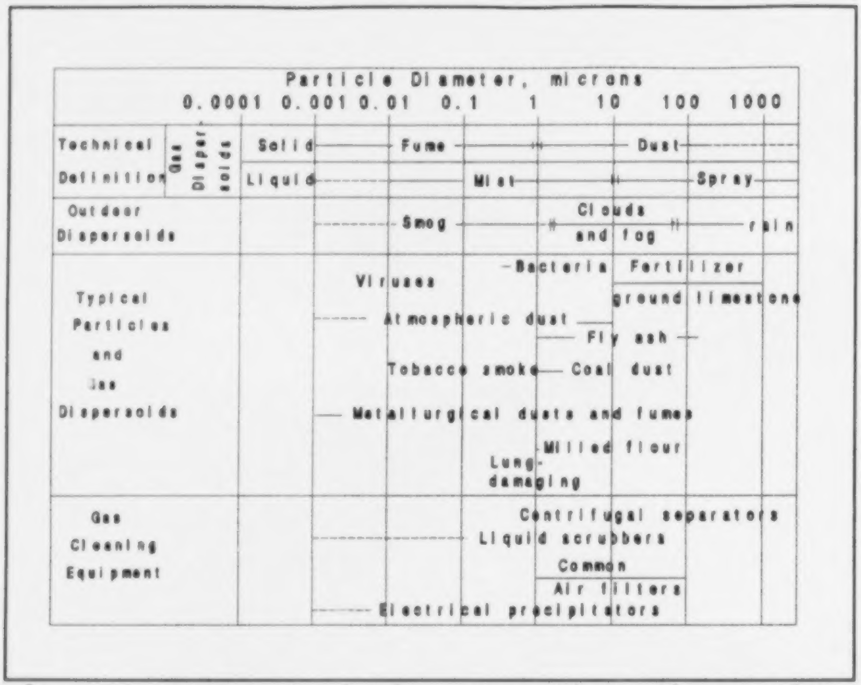

Figure 2.3 Characteristics of particle dispersoids. Adapted from Wark and Warner, (1981).

According to Figure 2.3, dust is defined as particles greater than 1 μm and includes particles such as: flyash, coal dust, lung-damaging dusts, bacteria and ground talc. Recommended industrial air cleaners for these types of dust are centrifugal separators, cloth collectors, high efficiency air filters, packed beds and electrostatic precipitators. As previously discussed, swine housing dust particles include particles less than 1 μm. The collection efficiency η as given by Equation (2-1), indicates the performance level of a gas cleaning device.

$$\eta = C\cdot A^{-1} = C\cdot(B+C)^{-1} = (A-B)\cdot A^{-1} \qquad (2\text{-}1)$$

where: η = collection efficiency,
A = dust concentration at inlet, particles/mL,
B = dust concentration at outlet, particles/mL, and
C = concentration of dust collected, particles/mL.

To account for the varying collection efficiencies of different particle sizes, the collection efficiency is generally given as a function of particle size. Figure 2.4 depicts the hypothetical fractional collection efficiency curve as a function of particle diameter.

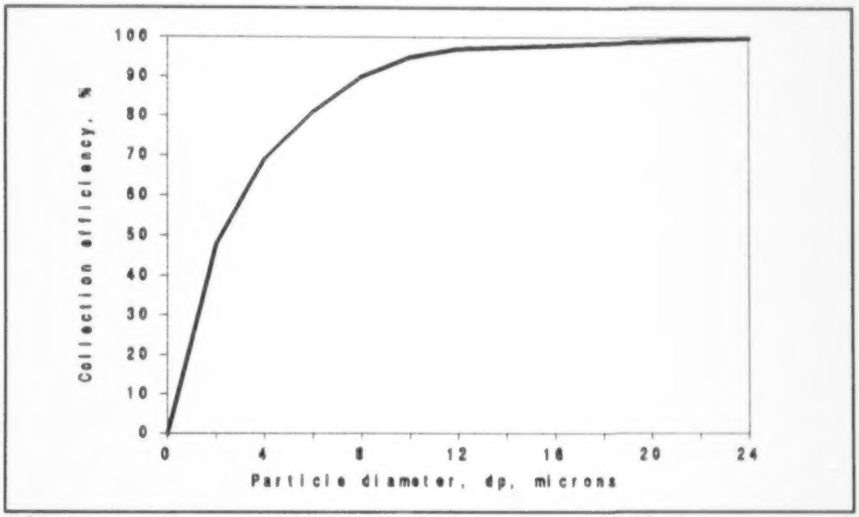

Figure 2.4 Fractional collection efficiency as a function of particle diameter. Adapted from Wark and Warner, (1981).

Equation (2-2) represents the overall collection efficiency based on particle number concentration, which is a summation of the particle concentration fraction for a given particle size multiplied by the fractional collection efficiency.

$$\eta_o = \Sigma(n_d \cdot \eta_d)\cdot(\Sigma(n_d))^{-1} \qquad (2\text{-}2)$$

where: η_o = overall collection efficiency, %,
n_d = particle concentration of size d,part/mL, and
η_d = collection efficiency for size range d, %.

2.5 Dust Removal by Electrostatic Precipitation

Applications. Electrostatic precipitators have been used in various industrial applications such as; fly ash removal from the stack exhaust of coal fired boilers, in kraft recovery boilers, and in petroleum plants for catalyst recovery. The advantages of using an electrostatic precipitator as opposed to other air cleaners are: 1)The capacity to handle large gas volumes; 2)high collection efficiencies even for particles less than 1 μm; 3)low energy consumption and draft loss and 4)the ability to operate with relatively high temperature gases (Wark and Warner, 1981).

Operating conditions. Industrial electrostatic precipitators have been designed for volumetric rates from 0.05 to 1888 m^3/sec and for removal of particles from 0.05 to 200 μm (Wark and Warner, 1981). The pressure drop through the collector is quite small, extending from 25 to 125 Pa. The gas temperatures and pressures that can be handled are generally up to 920 K and 1 MPa, respectively. For most applications, collection efficiencies range from 80 to 99%. The design of an electrostatic precipitator is dependent upon the size of the particles to be collected. Thus, higher efficiencies can be achieved if a small size range is to be collected. A prefilter such as a cyclone which can remove particles down to 10 μm is usually placed before the electrostatic precipitator.

Precipitator types. The two basic types of electrostatic precipitators include the tubular and wire-plate types. The tubular type precipitator includes a discharge wire within the grounded cylinder. This system is rarely used in industry since low dust concentrations and low gas flows are required to provide an adequate collection efficiency (Lloyd, 1988). The single-stage wire-plate type with negatively charged discharge wires are commonly used in industry. The preference of negative charge over positive charge is due to the quality of the corona discharge. The mobility of negative ions are higher than positive ions per unit applied voltage, leading to an expected lower collection efficiency with positive voltage (Lloyd, 1988).

However, positive voltage is often used in residential two-stage electrostatic precipitators. A single-stage precipitator is one in which particle charging and collection occurs within the same area of the precipitator. The two-stage type consists of discharge wires placed ahead of a series of alternately charged and grounded plates. A lower voltage can be used since charging occurs in both sections. The particles receive an initial charge as they pass between the discharge wires and grounded plates extruding from the collection section. As the partially charged particles pass between a charged and grounded collection plate, the charged plate repels the particles and causes them to accumulate upon the collection plate. This two-stage system using low positive voltage of approximately 6 kVDC, is used to reduce the production of ozone in residential units since any ozone in clean recirculated air acts as an irritant (McDonald and Dean, 1982).

The mechanisms involved. The four steps involved in the mechanism of electrostatic precipitation are: 1)The creation of an electric field and corona current; 2)particle charging; 3)particle collection and 4)removal of the collected dust (McDonald and Dean, 1982). The aforementionned mechanisms will be discussed for a single-stage wire-plate type precipitator, using negative potential with *positive* potential descriptions included in *italics*.

2.5.1 The Creation of an Electric Field and Corona Current

The formation of an electric field is accomplished by applying a large potential difference between a small-radius electrode and a much larger radius electrode, where the two electrodes are separated by a region of space containing an insulating gas (McDonald and Dean, 1982). In this discussion the small-radius discharge electrode is a small wire charged with high negative (*positive*) potential and the large radius electrode is a flat plate connected to ground, while the insulating gas is air. At any applied voltage, an electric field exists in the inter-electrode space (the space between the discharge and collector electrode).

For applied voltages less than the "corona starting voltage" a purely electrostatic field exists in the inter-electrode space. At voltages higher than the corona starting voltage, the electric field in the vicinity of the discharge wire is large enough to produce ionization by electron impact. Figure 2.5 depicts the mechanism of corona discharge.

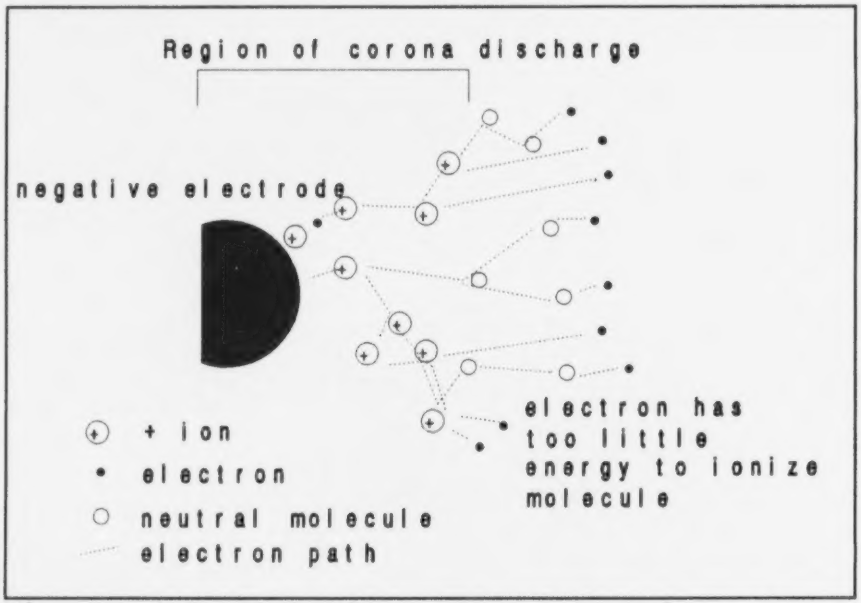
Region of corona discharge
negative electrode
electron has too little energy to ionize molecule
+ ion
electron
neutral molecule
electron path

Figure 2.5 Formation of a negative corona discharge. Adapted from Lloyd (1988).

The strong field surrounding the discharge wire distorts the orbits of the electrons in the atoms of the insulating gas so that only a small amount of energy is needed to ionize a gas molecule. As the negative (*positive*) discharge ionizes a neutral air molecule, the electrons and negative ions (*positive ions*) move away from the discharge wire at high accelerations while the positive ions (*negative ions and electrons*) migrate towards the discharge wire.

The high acceleration of the electrons and negative (*positive*) ions from the discharge wire, causes them to collide with neutral air molecules passing through the corona glow region. With each collision an extra electron and negative ion (*positive ion*) are released forming a stream of electrons (*positive ions*) called an electron (*positive ion*) avalanche. Once out of the corona region the electrons (*positive ions*) do not have sufficient energy to ionize any more neutral air molecules.

Corona discharge is not uniform over the surface of the discharge electrode, but appears as little tufts, starting at the tips of any spikes or irregularities, where the electric field is greatest. As the corona current increases, tufts spread rapidly along the electrode, becoming more numerous and more closely spaced. Due to the corona, electrons, negative ions and charged dust particles stream away from the discharge sites, colliding with neutral air molecules and driving them along causing the "electric wind" that blows from the discharge wire (Lloyd, 1988).

2.5.2 Particle Charging

Once the electrons (*positive ions*) are outside the corona region they drift toward the collection plate, forming an electric field extending from the discharge wire to the collection plate. The space-charge of the electric field is greatest at the discharge wire and decreases to zero at the collection electrode. If the inter-electrode distance is very small, the change in electric field is higher per unit distance than over a larger inter-electrode distance at a similarly applied potential. Therefore the space-charge present near the collection electrode is larger for a larger inter-electrode spacing (Lloyd, 1988).

There are two main mechanisms combined in the particle charging system: field and thermal charging (McDonald and Dean, 1982). Field charging is the process by which dust particles collect charged gas ions and electrons (*positive ions*). As the dust particles pass though the electrostatic precipitator they intercept the ions that make up the electric field. Figure 2.6 depicts the three stages of field charging.

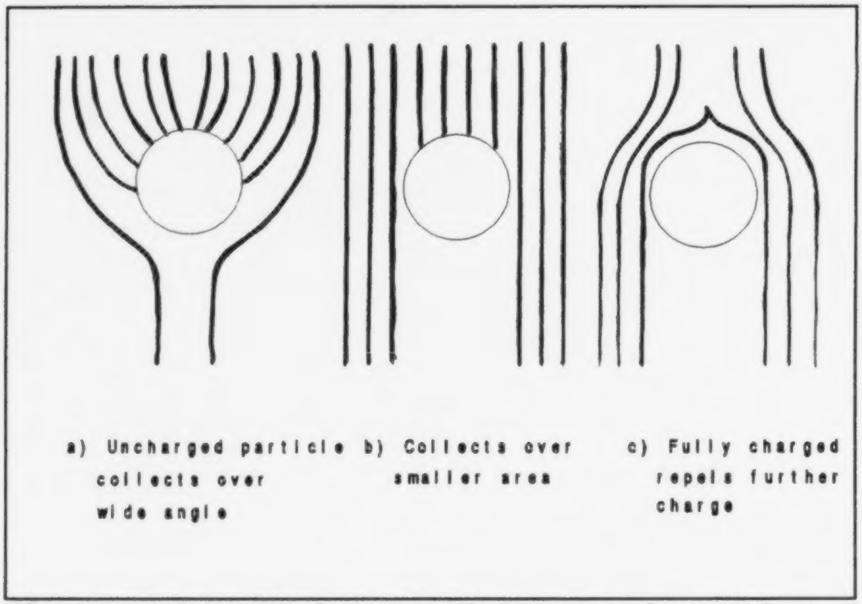
a) Uncharged particle collects over wide angle
b) Collects over smaller area
c) Fully charged repels further charge

Figure 2.6 Mechanism of field charging. Adapted from Lloyd (1988).

As the particle first enters the electric field it accepts charge from a wide angle over its surface as shown in Figure 2.6a. As the particle becomes partially charged it collects charge over a smaller area as in Figure 2.6b, until it is fully charged as in Figure 2.6c when it repels further charge (Lloyd, 1988). The rate at which a particle accepts charge, depends upon the current density in the space around the particle and the catchment area provided by the particle. The effective catchment area decreases as the particle becomes charged until when the saturation charge is reached, it becomes zero.

Thermal charging which is the main charging mechanism used by ionizers, depends upon collisions between particles and ions which have random motion due to their thermal kinetic energy (McDonald and Dean, 1982). The particle charging rate in this mechanism is determined by the probability of collisions between a particle and ions. If a supply of ions is available, such as produced by an ionizer, particle charging occurs even in the absence of an applied electric field. Charging by this mechanism takes place over the entire surface of the particle and requires a relatively long time to produce a limiting value of charge. This mechanism works well for particles less than 0.1 μm, regardless of the magnitude of the applied electric field, due to their small surface area and high mobility caused by Brownian motion (McDonald and Dean, 1982).

Generally the charge accumulation by a dust particle is a combination of field and thermal charging, depending upon the size of the dust particles and the strength of the field present.

2.5.3 Particle Collection

Once the particle is charged, it migrates to the plate electrodes, where dust collection occurs. The speed at which particle migration occurs is the migration or drift velocity, $\tilde{\omega}$ (Wark and Warner, 1981). This value depends upon the electrical force on the charged particle as well as the drag force developed as the particle moves, perpendicular to the main air flow, toward the collecting electrode. Migration velocity is directly proportional to the particle diameter and the square of the field strength and inversely proportional to the gas viscosity. The relationship between migration velocity and particle radius, as determined using tiny spheres of rubber is shown in Figure 2.7.

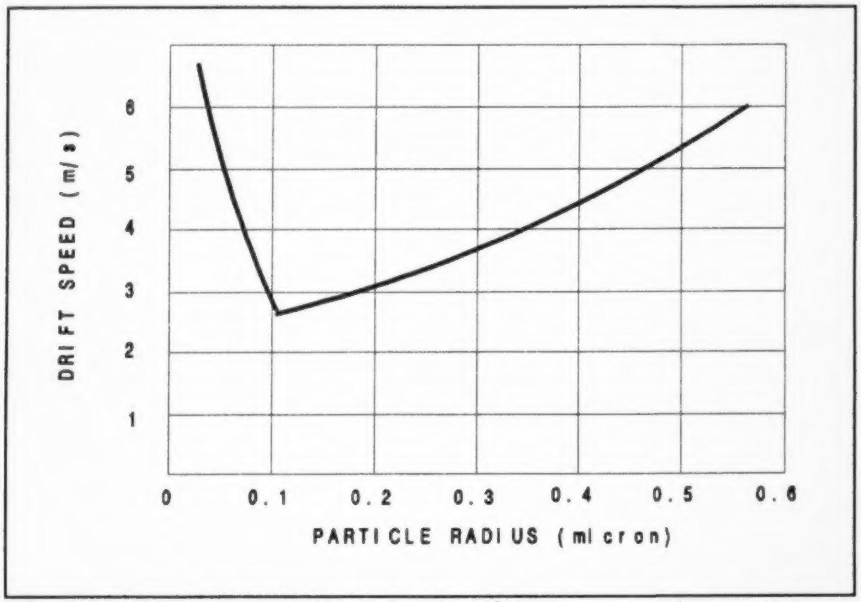

Figure 2.7 The effect of size upon the average migration velocity of a particle. Adapted from Lloyd, (1988).

According to Figure 2.7 there is a minimum of particle drift speed at a particle diameter of 0.2 μm. This drop in $\bar{\omega}$ is due to the motion of the particles. As was previously discussed, particles with diameter < 0.1 μm take on the motion of molecules as in Brownian motion (Lampman, 1974). Particles > 1 μm generally take the motion of the fluid in which they are suspended, according to Stoke's Law. The particles between 0.1 and 1 μm, should follow Stoke's Law, however due to their size they may not follow this flow due to slip and may escape uncollected. Due to their drift velocity, particles less than 0.1 and greater than 1 μm are generally collected with higher efficiencies than the particles between 0.1 and 1 μm.

For particles less than 5μm, the theoretical migration velocity is usually less than 0.3 m/s. For fly ash, the migration velocity lies typically between 0.01 to 0.2 m/s for the smaller particles present after prefiltering has been performed. An important parameter in electrostatic precipitation is the effective migration velocity (EMV), which is different from the average migration velocity. Effective migration velocity refers to the rate at which a particle makes its way towards the collecting electrode under the combined influence of the electrical and aerodynamic forces upon the particle. The term migration velocity generally is used to describe the drift speed of a certain particle size, whereas effective migration velocity is used for a dust having a distribution of particle sizes (Lloyd, 1988).

The electric field within the collected dust layer determines how well the dust layer will remain upon the collection electrode. Figure 2.8 depicts the electric field within the dust layer upon the collection electrode. A stream of ions and newly charged dust arrives continuously from the discharge electrodes, representing an electric current of between 0.1 and 0.5 mA/m^2 of collecting surface (Matts, 1989). The current must pass through the layer of dust in order to reach the collection electrode. The resistivity of the dust results in a voltage drop over the dust layer and the creation of an electric field within the dust. Using Ohm's law expressed in Equation 2-3, the strength of the electric field within the dust layer can be determined from the dust resistivity and current density.

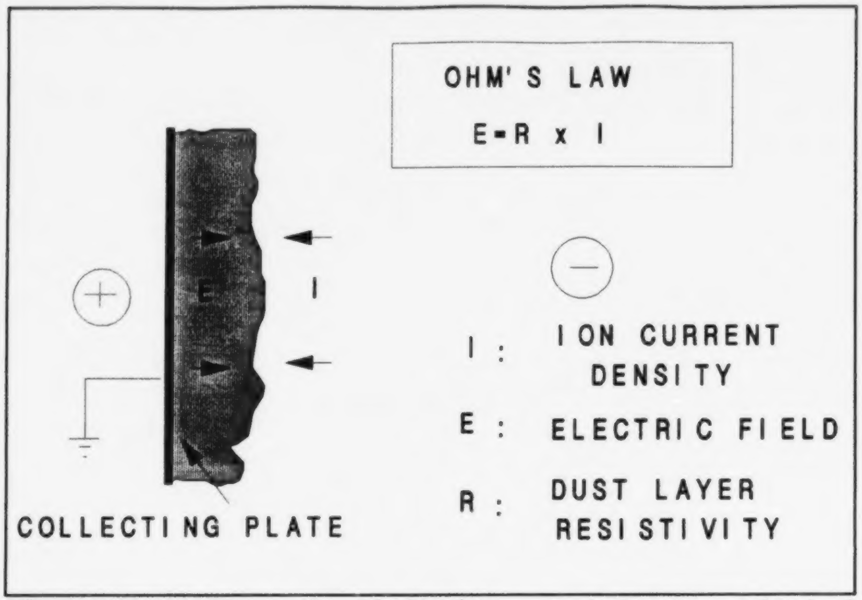

Figure 2.8 Electric field in a dust layer. Adapted from Matts, (1989).

$$E = R \cdot I \qquad (2\text{-}3)$$

where: E = strength of the electric field, $V \cdot m^{-1}$,
R = resistivity, $Ohm \cdot m$, and
I = current density, $A \cdot m^{-2}$.

The current flows through the dust layer via two mechanisms: 1)Surface and 2)volume conduction (McDonald and Dean, 1982). Surface conduction, the main component of current flow at gas temperatures less than 80°C is the flow of current along the surface of dust particles, and occurs especially in dusts of high moisture content, since the current is readily conducted by water molecules (McDonald and Dean, 1982). Volume conduction represents the flow of ions through the bulk of the dust layer, and generally is the main component of current conduction at air temperatures greater than 149°C (McDonald and Dean, 1982).

Dust not only accumulates upon the collection electrodes, but also upon the discharge electrodes. Dust accumulates in the form of sausages around the discharge wire, in between the tufts produced by the corona. The electric wind from these tufts prevents the build-up of dust particles at these points. The precipitator performance suffers due to the uneven distribution of the corona, even if the overall corona current is unchanged (Lloyd, 1988).

2.5.4 Removal of Dust from the Collection Electrode

There are generally two types of accepted cleaning mechanisms used for electrostatic precipitators: 1)Rapping and 2)washing or dry cleaning of the collection electrodes. The first mechanism is used for industrial-sized electrostatic precipitators whereas the second method is only used for the residential, small-sized electrostatic precipitators. In residences, dust loading is such that cleaning of the collector is required once per month. In industry, however, the dust loadings are such that cleaning is required more often and the entire system must continue to operate during the cleaning operation.

A rapper is a device that strikes the collection or discharge electrode with a force sufficient to remove the dust layer from its surface. Rapping removes the collected dust from the electrodes so that it can fall into a storage hopper below while allowing as little as possible of the dust to be re-entrained into the airstream. The way in which rapping removes the dust depends upon the cohesivity of the dust. Small particle size and high resistivity causes dust to cohere well. Dusts that cohere well tend to stay together when rapped, falling as sheets into the hopper.

Rapping can occur using five different mechanisms: 1) Displacement of the electrodes; 2)vibrators; 3)drop hammers; 4)solenoids and 5)pneumatics (Lloyd, 1988). The acceleration that an electrode undergoes during rapping is transmitted by shear forces through the layer of dust. Since the layer of the dust nearest the electrode must sustain the greatest shear force (that needed to accelerate the overlying layers of dust), the cohesive bond is often broken. The outer layers of dust fall away leaving a residual coating.

Using the mechanism of displacement of electrodes, the whole collection electrode is pivoted about one corner and allowed to swing under gravity until its lower corner strikes an anvil, located beneath the pivot point. This system is not often used since dust tends to collect in the slots in which the plates are located, limiting them from swinging freely.

Vibrators are not used often since they were deemed inefficient in tubular precipitators. Vibration is achieved by using a 100 or 120 Hz signal to drive a solenoid or by using an electric motor to rotate an eccentric mass. The frequency of vibration in either case is so low that large amplitudes are required to give adequate acceleration to the electrodes. Vibrators may be used on discharge electrodes since they are generally less massive than collection electrodes.

Drop-hammers are the most commonly used type of rapper. The two types that are effective and in general use are the cam-driven drop-hammer and the flail. The cam-driven drop-hammer remains out of the main gas flow and strikes the top of the collection electrodes. The flail on the other hand employs a rotating shaft which periodically turns toward the base of a row of collection electrodes until the rapping shaft strikes the collection electrodes. This system can also be used to remove the dust from the discharge electrodes, by striking the entire discharge electrode frame.

A solenoid-driven rapper includes a solenoid used to lift a plunger which then falls under its own weight against an anvil at the top of a long push rod which strikes the collection electrodes. The pneumatically driven system is similar to the solenoid driven-rapper except that the actuators are pneumatically driven instead of electrically driven. Both of these systems can be altered during operation of the precipitator until the best combination of frequency and intensity of blows is found.

The disadvantage resulting from rapping is re-entrainment of dust particles back into the airstream. If the particles do disperse as in a cloud instead of falling in a sheet they could short-circuit the electrostatic precipitator, causing the power supply to be disrupted for a short period. During this time many of the dust particles would be re-entrained, decreasing the collection efficiency of the electrostatic precipitator.

In residential-type electrostatic precipitators it is recommended that the collection cells be removed once per month and washed with water and mild detergent. The collection cells must be thoroughly dried before being put back into operation. A dry method of cleaning includes removing the dust layer using a cloth, wiper or brush along the surface of the electrodes. Both of these methods require that the cleaning unit be removed from service.

2.6 Factors Affecting Precipitator Performance

The various factors that influence the design, operating conditions and collection efficiency of an electrostatic precipitator include: 1)The resistivity of the dust particles; 2)the temperature, pressure, velocity and type of gas; 3)inlet dust burden; 4)electrode spacing and 5)particle size (Lloyd, 1988).

2.6.1 Electrical Resistivity

Electrical resistivity is defined as the resistance to current flow, through a dust sample 1 cm in thickness contained in a cubic volume, when exposed to an electrical voltage equivalent to 85-95% of the "breakdown voltage" of the sample, applied uniformly across two opposite faces of the cube (McDonald and Dean, 1982). The three ranges of specific dust resistivity are: 0 to 10^4 Ω·cm (low); 10^4 to $2x10^{10}$ Ω·cm (medium); and above $2x10^{10}$ Ω·cm (high) (Batel, 1976).

The optimum operating voltage and current of an electrostatic precipitator for a dust of "medium" electrical resistivity is selected as 85 to 95% of that voltage at which "breakdown" occurs. Breakdown can either occur in the air in the inter-electrode space (sparking or arcing) or in the dust layer as in back corona. In a clean precipitator, sparking or arcing occurs when the applied voltage supplies a current that is too high for the inter-electrode spacing. The energy in the inter-electrode space causes the air molecules to breakdown into electrons and positive ions resulting in the propagation of a spark across the inter-electrode space.

A dust with "low" electrical resistivity from 0 to 10^4 Ω·cm, loses its charge as soon as it touches the collection electrode. Such low resistivity can impede dust collection since, at a given voltage a larger current is required to supply the electric field required to hold the dust onto the collection plate. This higher-than-normal current may result in the sparking that can occur if the local current density is too high for a specific discharge-to-collection electrode spacing. If the required electric field is not produced using a higher current to compensate for the lower resistivity, the particles will easily be re-entrained back into the airstream, resulting in lower collection efficiency.

A dust with a "high" electrical resistivity, greater than 2×10^{10} $\Omega\cdot$cm, can impede dust collection by either producing an extreme field force effect or back corona. The field strength within the inter-electrode space becomes higher than normal and can result in pockets of dust accumulating upon the collection electrode. The dust layer becomes uneven and can interfere with the supply of current. A stronger rapping force would be required to remove the highly resistive dust from the collection electrode.

An abnormally high field strength within the dust layer can lead to a corona-like discharge within the dust layer, producing large quantities of positive and negative ions. The phenomenon of back-corona is shown in Figure 2.9.

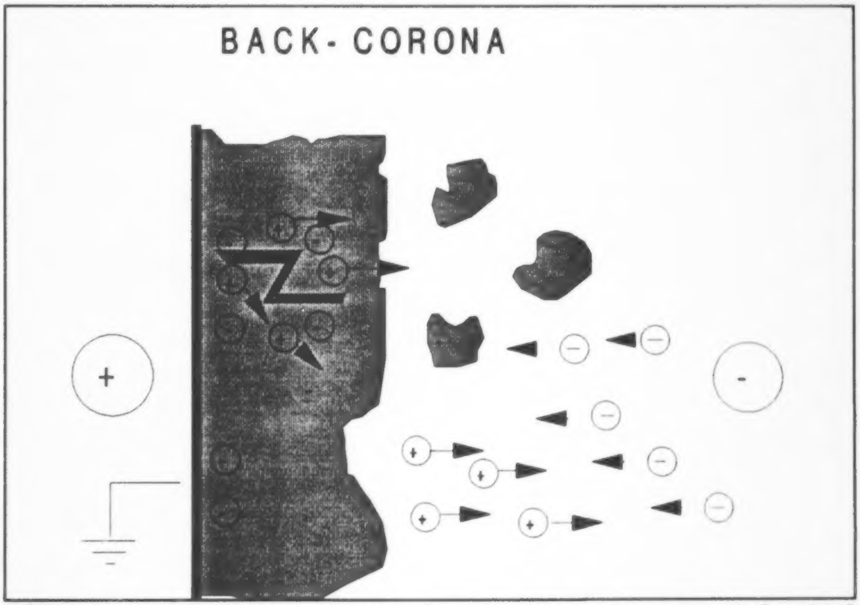

Figure 2.9 Back-corona in a dust layer. Adapted from Matts, (1989).

The negative ions (*positive ions*) quickly move toward the collection plate while the positive ions (*negative ions*) are attracted into the inter-electrode space, while migrating back to the discharge wire. Within the inter-electrode space, there are negative ions (*positive ions*) from the corona discharge and positive ions (*negative ions and electrons*) from the back-corona in the dust layer. These ions of opposing polarity neutralize each other so that the charging of the dust is impeded. Reducing the supplied current to compensate for the high resistivity of the dust can result in a deficiency in current for the production of a strong corona surrounding the discharge wires. Both the back corona and a decrease in the applied current can limit the collection capacity of the electrostatic precipitator.

A dust of "medium" resistivity, from 10^4 to 2×10^{10} $\Omega \cdot$cm, is ideal since the required current to supply a sufficient electrical field to hold the dust onto the collection electrode is high enough to create a strong corona discharge yet low enough to not cause sparking or back corona. Figure 2.10, represents the relationship between electrical resistivity and the effective migration velocity of a dust particle. Dusts of medium resistivity were shown to yield the highest values of effective migration velocity (Lloyd, 1988). The standard technique for determining laboratory resistivity values for the measurement of the bulk resisitivity of fly ash was established in Power Test Code 28 (PTC-28), by the American Society of Mechanical Engineers (ASME) (McDonald and Dean, 1982). This technique was used to determine the bulk electrical resistivity of several organic dusts (Fournier and Feddes, 1991). These included swine housing dust, flour, corn starch, icing sugar and milk powder. The swine housing dust had a size range of 0.5 to 10 μm, with 59.4% and 38.5% of the particles being in the size ranges of 0.5 to 1 μm and 1 to 2 μm, respectively (Fournier and Feddes, 1991). The average moisture content of the dust was 2.4%, wet basis. The resistivities, determined at two dust layer thicknesses of 0.5 and 1 cm were 5.17×10^8 and 2.53×10^8 $\Omega \cdot$cm, respectively

(Fournier and Feddes, 1991).

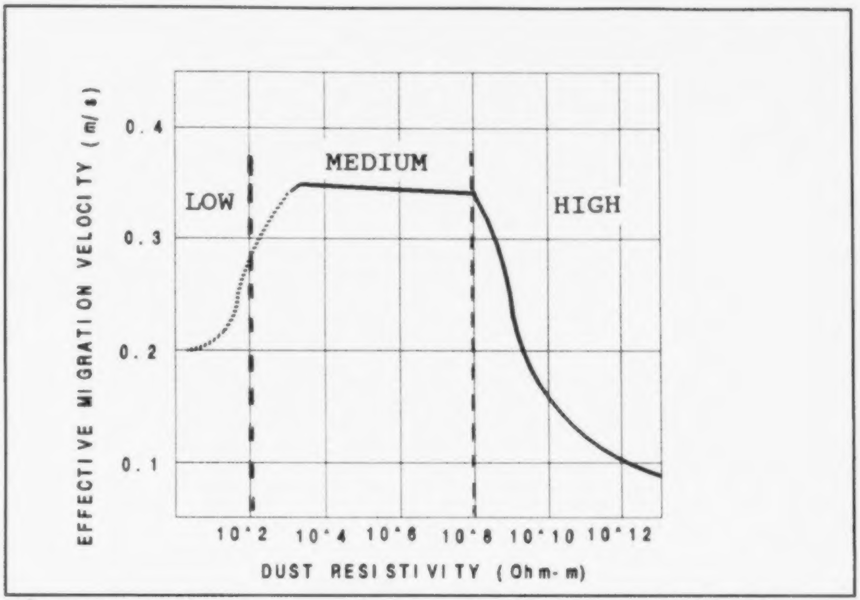

Figure 2.10 The effect of dust resistivity on effective migration velocity. Adapted from Lloyd, (1988).

The resistivity values of swine housing dust at two dust thicknesses were both within the medium resistivity range. However, converse with the other organic dusts tested, the resistivity decreased with increasing dust thickness. The calculation of resistivity is given by equations 2-4 and 2-5. Equation 2-4 is used to determine the resistance to current flow using 85% of the voltage and current at which sparking within the dust layer occurred. The resistivity is determined in Equation 2-5, using the resistance to current flow, the contact area of the dust and electrode, and the thickness of the dust layer. Although dust layer thickness is included in the calculation of resistivity, it does affect the response of the dust to an applied voltage.

$$R = V \cdot I^{-1} \qquad (2\text{-}4)$$

where: R = resistance to current flow, Ω,
V = 85% of sparkover voltage, VDC, and
I = 85% of sparkover current, A.

$$\rho = R \cdot A \cdot l^{-1} \qquad (2\text{-}5)$$

where: ρ = resistivity of dust layer, $\Omega \cdot cm$,
R = resistance to current flow, Ω,
A = surface area of dust layer, cm^2, and
l = dust layer thickness, cm.

As the dust layer thickness is increased, the applied voltage required to maintain sufficient current through the dust layer is also increased. In the case of swine housing dust, the current was propagated by the increased voltage through a spike formation in the dust. The spike was a breakdown in the dust layer resulting from an excessive electric field within the dust layer. The current passing through the center of the hollow spike of dust was very high resulting in a lower resistance ratio than that calculated at a lower dust thickness.

On the basis of these tests, it was concluded that electrical breakdown was likely to occur within swine housing dust if the electric field was increased from 400 to 600 VDC per mm of dust layer thickness. Frequent cleaning could decrease the chance of back-corona and prevent the performance of the electrostatic precipitator from being impaired. Of the other organic dusts tested, flour gave the highest collection efficiency in an residential electrostatic precipitator. The flour also had the highest moisture content, at 6.0% wet basis (Fournier and Feddes, 1991). This dust demonstrated the least amount of influence on electrical resistivity due to difference in dust thickness. Within the electrostatic precipitator as the dust accumulated, the current continued to flow through the dust layer via surface conduction with little added resistance. This may be due to the higher moisture content, which allows for better current conduction.

2.6.2 The Deutsch-Anderson Theory

The assumptions used to derive the following theory are: 1)The gas-dust mixture is uniform over each cross-section of the precipitator and 2)each unit length of the precipitator behaves exactly the same as every other unit length of the precipitator (Lloyd, 1988). The complete derivation relating the collection efficiency to the migration velocity is given in Appendix A.

The Deutsch-Anderson relationship, which can be expressed in many ways is given in Equations 2-6 and 2-7. Slip ($), is the fraction of dust entering a precipitator that escapes. Specific collection area is the area of collecting electrode per unit volume of gas that flows through the electrostatic precipitator per second.

$$\$ = \exp\,(-\ \text{ὠ}\cdot A) \tag{2-6}$$

where: $ = slip, fraction of uncollected dust,
ὠ = effective migration velocity, $m\cdot s^{-1}$, and
A = specific collection area, $m^2\cdot s\cdot m^{-3}$.

This may be rewritten as :

$$\$ = \exp\,(-\ \text{ὠ}\cdot L\cdot v^{-1}\cdot S^{-1}) \tag{2-7}$$

where: $ = slip, fraction of uncollected dust,
ὠ = effective migration velocity, $m\cdot s^{-1}$,
L = length of the precipitator, m,
v = gas velocity, $m\cdot s^{-1}$, and
S = inter-electrode spacing, m.

A modified version of the Deutsch-Anderson theory has been developed to give a more accurate prediction of electrostatic precipitator behavior (Lloyd, 1988). The terms basically remain the same except for the effective migration velocity which is shown in Equation 2-8, where the modified effective migration velocity is called ω_k.

$$\omega = (\omega_k \cdot A)^{0.5} \cdot A^{-1} \qquad (2\text{-}8)$$

where: ω = effective migration velocity, $m \cdot s^{-1}$,
ω_k = modified EMV, $m \cdot s^{-1}$, and
A = specific collection area, $m^2 \cdot s \cdot m^{-3}$.

The modification was developed for the following reason; since the effective migration velocity is related to the size of the dust particles, the particles with the greatest migration velocity, (the largest and smallest particles), are collected close to the precipitator inlet. Slightly downstream of the inlet, the next largest and the next smallest particles, having smaller drift speeds are collected. Due to this occurrence, the effective migration velocity of the dust particles is a function of the length of a precipitator.

Therefore the assumption used in the Deutsch-Anderson relationship, that effective migration velocity is independent of specific collecting area, which includes the length, is not valid (Lloyd, 1988). The average and effective migration velocities decrease uniformly throughout the length of the precipitator, from the inlet to the outlet. A factor was applied to the Deutsch-Anderson relationship to better represent the collection performance of the precipitator. Equations 2-9 and 2-10, give the modified version of the relationship between slip and migration velocity, ω_k, and the specific collection area:

$$\$ = \exp\,(-\,\omega_k \cdot A)^{0.5} \qquad (2\text{-}9)$$

where: $\$$ = slip, fraction of uncollected dust,
ω_k = modified EMV, $m \cdot s^{-1}$, and
A = specific collection area, $m^2 \cdot s \cdot m^{-3}$.

Which can be written as:

$$\$ = \exp\left(- \tilde{\omega}_k \cdot L \cdot v^{-1} \cdot S^{-1}\right)^{0.5} \qquad (2\text{-}10)$$

where: $\$$ = slip, fraction of uncollected dust,
$\tilde{\omega}_k$ = modified effective migration velocity, $m \cdot s^{-1}$,
L = precipitator length, m,
v = gas velocity, $m \cdot s^{-1}$, and
S = inter-electrode spacing, m.

The actual collection efficiency of an electrostatic precipitator using the original and modified versions of the Deutsch-Anderson relationship are given in Equations 2-11 and 2-12.

$$\eta = 100 \cdot \left(1 - \exp\left(- \tilde{\omega} \cdot L \cdot v^{-1} \cdot S^{-1}\right)\right) \qquad (2\text{-}11)$$

where: η = collection efficiency, %,
$\tilde{\omega}$ = effective migration velocity, $m \cdot s^{-1}$,
L = precipitator length, m,
v = gas velocity, $m \cdot s^{-1}$, and
S = inter-electrode spacing, m.

$$\eta_k = 100 \cdot \left(1 - \exp\left(-\left(\tilde{\omega}_k \cdot L \cdot v^{-1} \cdot S^{-1}\right)^{0.5}\right)\right) \qquad (2\text{-}12)$$

where: η_k = modified collection efficiency, %,
$\tilde{\omega}_k$ = modified effective migration velocity, $m \cdot s^{-1}$,
L = precipitator length, m,
v = gas velocity, $m \cdot s^{-1}$, and,
S = inter-electrode spacing, m.

The following effects on effective migration velocity were determined using the aforementionned theories. The operating voltage and current at which a corona appears may change according to type of gas used and its temperature and pressure. The electrical mobilities of singly charged positive and negative gas ions at $0^{\circ}C$ and 101.3 kPa, for dry air are 1.36 and 2.1 $m^2/(s \cdot V) x10^{-7}$ (Oglesby and Nichols, 1978). The mobility value of the negative air ions is greater than that for Cl_2, CO_2, HCl, H_2O, H_2S, NH_3 and SO_2, at the same conditions. Thus. it would be expected that the corona starting voltage for air would be lower than these gases at a similar temperature and pressure.

Temperature and pressure do modify corona starting and sparkover potentials. Since the avalanche process is brought about because electrons have sufficient time between collisions to be accelerated to a velocity sufficient to ionize the gas, the potential necessary to initiate corona is related to the density of the host gas. If the gas pressure (and thus density) is increased, the molecules are effectively moved closer together, resulting in a shortened mean free path and reduced mean free time between collisions. The reduced time between collisions requires a greater electric field to accelerate the electron to the ionization velocity.

An increase in pressure at a given temperature results in an increased density while an increase in temperature at constant pressure results in a decrease in gas density. Figure 2.11 demonstrates the experimental relationship between the corona starting voltage, and gas pressure and temperature.

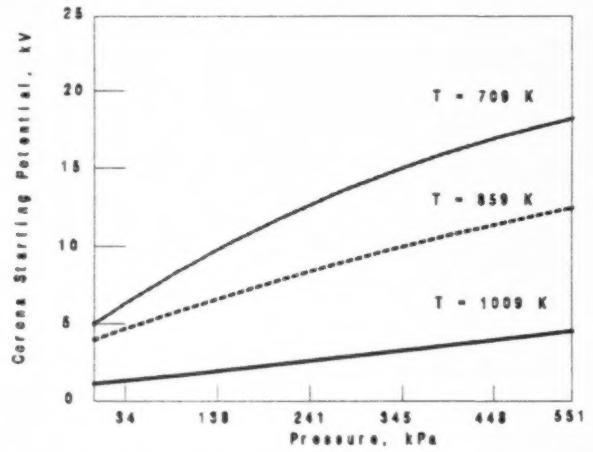

Figure 2.11 The effect of gas temperature and pressure upon corona starting voltage. Adapted from Oglesby and Nichols, (1978).

The lower corona starting voltages occur for higher gas temperatures. At the gas temperature of 709 K an increase in pressure from 0 to 551 kPa yielded a larger difference in corona starting voltage, than occurred for the same pressure changes at higher gas temperatures.

Provided the average electric field between the discharge and collection electrode is kept constant, the effective migration velocity increases with the distance between electrodes (Lloyd, 1988). This may be due to the effect on the electric field near the collection electrode of the space-charge. The larger the inter-electrode spacing, the larger the space-charge and therefore the greater the field near to the collecting electrodes. Figure 2.12 shows the approximate relationship of effective migration velocity with the spacing between the collection electrodes or twice the inter-electrode spacing. The effective migration velocity was found to rise proportionately with the inter-electrode distance up to a spacing of 0.5 m (Lloyd, 1988).

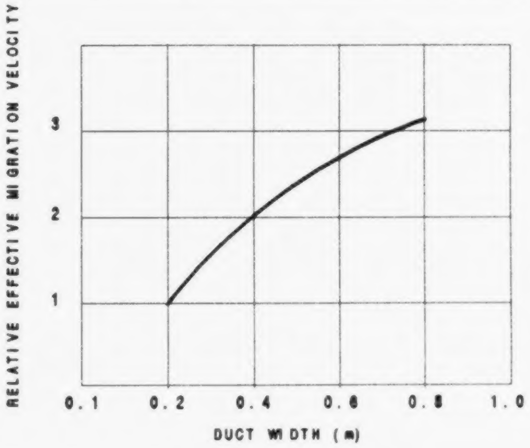

Figure 2.12 The effect of duct width or inter-electrode spacing upon effective migration velocity. Adapted from Lloyd, (1988).

The effect of the inlet dust load upon the effective migration velocity is shown in Figure 2.13. This may be due either to the charge carried by the particles or to an increase in mean particle size (Lloyd, 1988). The greater the inlet dust burden, the greater the space-charge and the more the electric field is enhanced close to the collection electrode. It was also found that, as inlet burden increased, so did the mean particle size and, thus, the effective migration velocity.

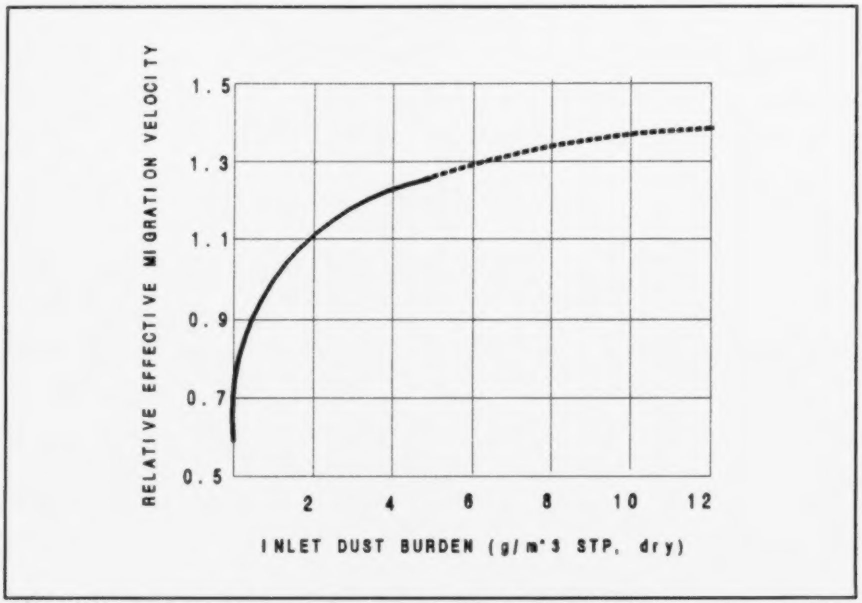

Figure 2.13 The effect of inlet dust burden upon effective migration velocity. Adapted from Lloyd, (1988).

The effect of gas velocity on effective migration velocity is shown in figure 2.14. Two types of effective migration velocity are shown, the Deutschian, ω, and the modified Deutschian, ω_k. The gas flow through the precipitator is the most important parameter that influences the performance of a precipitator, next to the applied potential. Gas velocity is calculated from the volume of gas that flows through the precipitator and the inside cross-sectional area of the precipitator. If the effective migration velocity, $\tilde{\omega}_k$, is used, the maximum occurs at a gas velocity of 1.5 m/s. These values are approximate because the actual values of the effective migration velocity and the peak gas velocities depend upon the design of the precipitator and the nature of the dust.

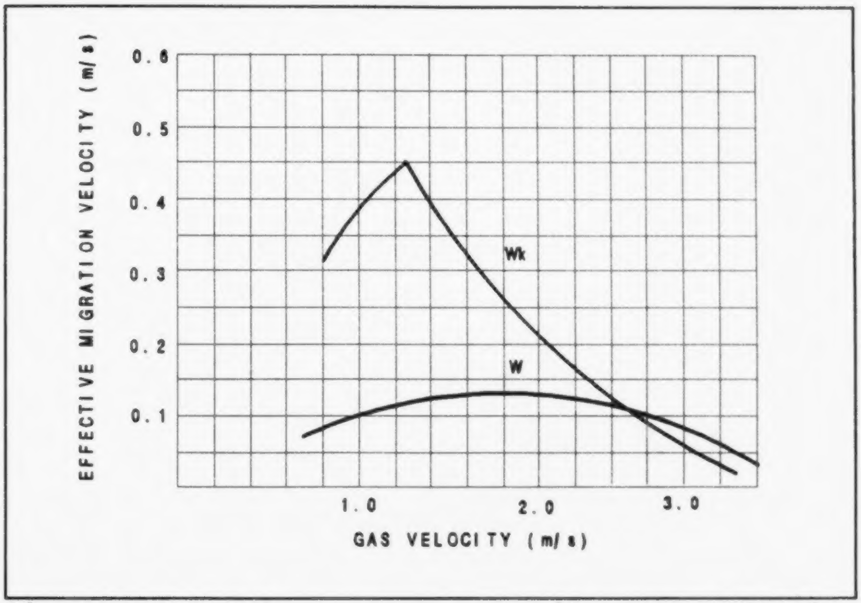

Figure 2.14 Effect of gas velocity upon effective migration velocity. Adapted from Lloyd, (1988).

It was discussed earlier how the particle size of the dust affects the migration velocity. However the influence on effective migration velocity is different as is shown in Figure 2.15. In each case migration velocity is at a minimum at a particle diameter of 0.1 μm. However, with increasing particle diameter, the curve of the effective migration velocity rises asymptotically to a limiting value, with increasing particle diameter (Lloyd, 1988). This curve is derived from experiments performed with a pilot precipitator in which the collection efficiency was found to be a function of particle diameter.

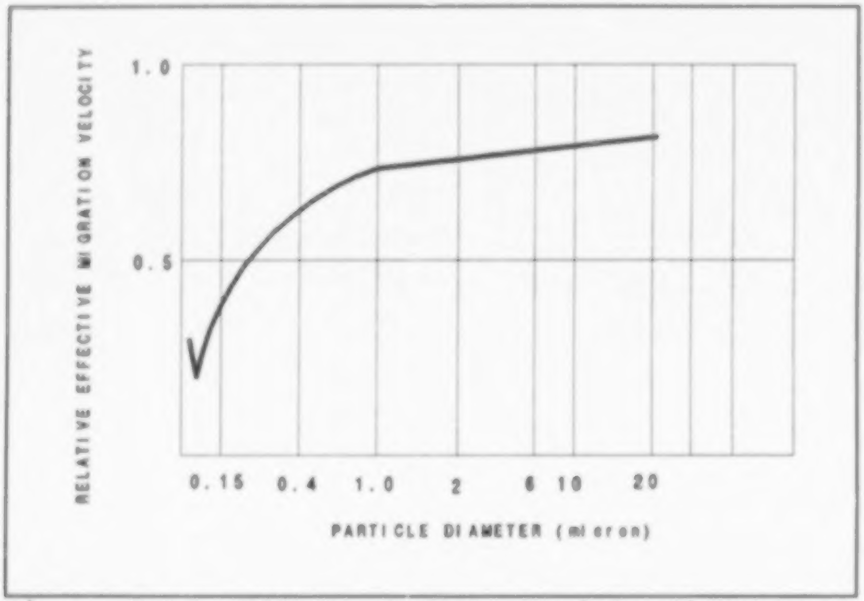

Figure 2.15 Effect of dust particle diameter on effective migration velocity. Adapted from Lloyd, (1988).

2.7 Disadvantages of Using Electrostatic Precipitation

If the operation of the electrostatic precipitator is controlled and monitored responsibly, the potential hazards are very few. Three possible hazards produced by electrostatic precipitation are: 1) Excessive ozone production; 2) fire or explosion and 3) electrical shocks (McDonald and Dean, 1982).

2.7.1 Ozone

Ozone is a natural by-product of high voltage equipment (Klein et al., 1973). Ozone (O_3), is generated when an oxygen molecule is sufficiently excited to dissociate into atomic oxygen (O) which undergoes further collisions with oxygen molecules (O_2) to cause the formation of the ozone molecule. The human body is very sensitive to ozone, capable of detecting its odor at 0.02 ppm. Nasal and throat irritations occur at 0.3 ppm. At a concentration of 1 ppm, severe restriction of respiratory passages occurs and many persons have a low tolerance of higher concentrations (McDonald and Dean, 1982). Ozone can damage lung tissue by accelerating the aging process, making it more susceptible to infection. The two TLV's recommended by the ACGIH are 0.1 ppm and 0.3 ppm, for an 8-h day, 40-h week and the maximum not to be exceeded for more than 15 minutes, respectively (ACGIH, 1985).

Another reason to maintain low concentrations of ozone, is that it is very corrosive and can damage the material within the electrostatic precipitator. Ozone is a very unstable molecule. Therefore, when an ionization source is eliminated, the ozone quickly breaks down and concentrations tend toward zero. Ozone has two advantageous uses, for disinfection and to eliminate odors, as long as the ozone production is kept out of the human and animal's breathing environment (Klein et al., 1973).

2.7.2 Fire or Explosion Hazards

Many of the dusts handled within industry or agriculture are combustible and care must be taken to avoid explosions. The factors which distinguish an explosion from a fire are included in the fire triangle and the explosion pentagon (Amyotte et al, 1988). The fire triangle consists of fuel, oxidant and an ignition source. The explosion pentagon includes the three components present in the fire triangle with the addition of the following: thorough mixing of the fuel and oxidant, and confinement of the combustible mixture. Since the occurrence of sparking within electrostatic precipitators is common, a fire or explosion can be ignited.

The explosibility of swine housing dust was determined at two dust concentrations: 0.3 and 0.4 kg/m^3 in the presence of medium turbulence (Fournier and Feddes, 1991). The dust was determined to be explosive at both of these concentrations having been ignited in a pressurized chamber by a chemical source having a stored energy of 10 kJ. Even though these concentrations are approximately 50 000 times the average concentration of dust particles present in a swine confinement building, they may occur within the electrostatic precipitator duct or storage hopper. Realizing the hazard potential, the pressure within the dust and the hopper should be kept low and the turbulence with which the dust travels through the entrance into the storage hopper, should be reduced.

2.7.3 Electrical Shock

Several safety precautions should be employed when working around an electrostatic precipitator. If at all possible, the entire unit should be shielded completely from animals and humans. If the unit is to be serviced, it should be turned off and the current must reach zero, before it is opened and handled. Pure direct current produces a steady sensation of intense heating and burning along the current path with only slight muscular contraction. A direct current flow of 10 mA through the body causes little or no sensation, however secondary hazards such as falling due to sudden shock are possible (McDonald and Dean, 1982). The electrostatic precipitator casing should be properly insulated to ensure it is not conducting current.

3. OBJECTIVES

Due to the potentially harmful effects swine housing dust can have upon animals and stockpersons, an efficient, low maintenance and inexpensive dust removal system is required within swine confinement buildings. Combining an air cleaning system with a recirculation duct enables the dust within the room to pass through the air cleaner. Until now a self-cleaning, highly efficient electrostatic precipitator has not been designed specifically for swine confinement buildings. From the literature, airspeed and potential appear to be the parameters that have the greatest effect on dust removal. The overall aim of the project was to evaluate the effect of applied potential and airspeed through the electrostatic precipitator upon the collection ability of the unit.

A prototype of an air cleaner was fabricated based upon the design of industrial type electrostatic precipitators. A self-cleaning mechanism was not included in the prototype. The particle charging and collection components of the electrostatic precipitator should be properly selected and designed before a cleaning mechanism is added. The primary objectives of the experiment, were:

1. To calculate the dust collection efficiency of the prototype in an environmental chamber at three voltage and airspeed levels,
2. To calculate the effective migration velocity of the dust at the different voltage and airspeed levels, using the modified Deutsch-Anderson equation,
3. To calculate the expected collection efficiency at different inter-electrode spacings and precipitator lengths, and,
4. To measure the ozone production at different applied voltages.

4. ELECTROSTATIC PRECIPITATOR DESIGN

4.1 Industrial Designs

A typical industrial type electrostatic precipitator used in the removal of fly ash from coal fired boilers' exhaust is shown in Figure 4.1. The electrostatic precipitator is a wire-plate type and generally consists of the following nominal dimensions:

Height : 9 - 12.5 m
Length : 12 - 16 m
Inter-electrode distance : 0.2 m
Applied potential : 50.0 kV
Corona current : 0.3 A
Gas Velocity: 1 - 1.6 m/s
Approximate collecting area connected to one rectifier (power supply): 1500 - 3600 m^2
Operating Gas Temperatures: 150 - 700 ^{o}C
(Matts, 1989; Lloyd, 1988).

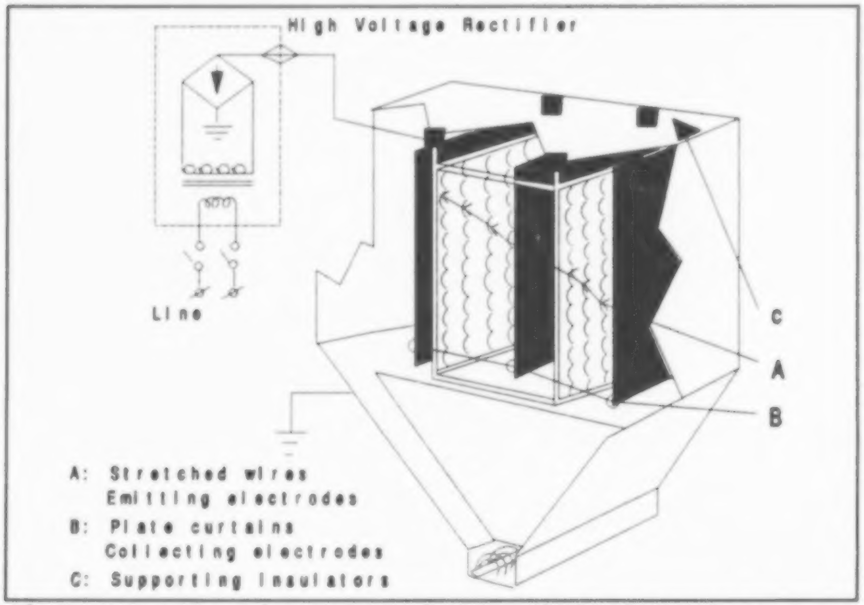
High Voltage Rectifier
Line
C
A
B
A: Stretched wires
Emitting electrodes
B: Plate curtains
Collecting electrodes
C: Supporting insulators

Figure 4.1 Section of an industrial wire-plate type electrostatic precipitator. Adapted from Matts, (1989).

In the industrial-type precipitators the discharge wire frame is a rigid box-like structure. Discharge electrodes are of spiralized stainless steel wire (2.5 - 2.7 mm). Collecting electrodes are generally cold-rolled strips (0.4 m wide). Tumbling hammer rapping mechanisms are used for the discharge and collection electrodes (Matts, 1989). The control of applied voltage and current are generally based upon 50 - 100 sparks per min. (Lloyd, 1988).

4.2 Prototype Design

The design selected for the prototype was based on the aformentioned type of precipitator. The limitations applied to the prototype included: 1)Must be sized to fit an existing recirculation duct and 2)must be easily assembled and disassembled. The selection of the materials was agreed upon with the Engineering Services Branch of Alberta Agriculture. The stainless steel wires and galvanized steel collection plates were selected for their strength and resistance to corrosion as compared to aluminum. The operating parameters such as the applied voltage and airspeed through the precipitator were selected after the design was completed.

The electrostatic precipitator prototype was a single-phase wire-plate type using negative potential. The three main components of the prototype were as follows: 1)The particle charging mechanism; 2)the particle collection mechanism and 3)the precipitator enclosure.

The particle charging mechanism included: a)The discharge wires and frames; b)the high-voltage power supply and c)the high-voltage bus bar. The particle collection mechanism included: a)The collection plates and b)the grounded bus bar. The precipitator enclosure consisted of a plywood duct which connected the electrostatic precipitator with the recirculation fan and duct. The front and side views of the prototype as shown in Figures 4.1 and 4.2, respectively.

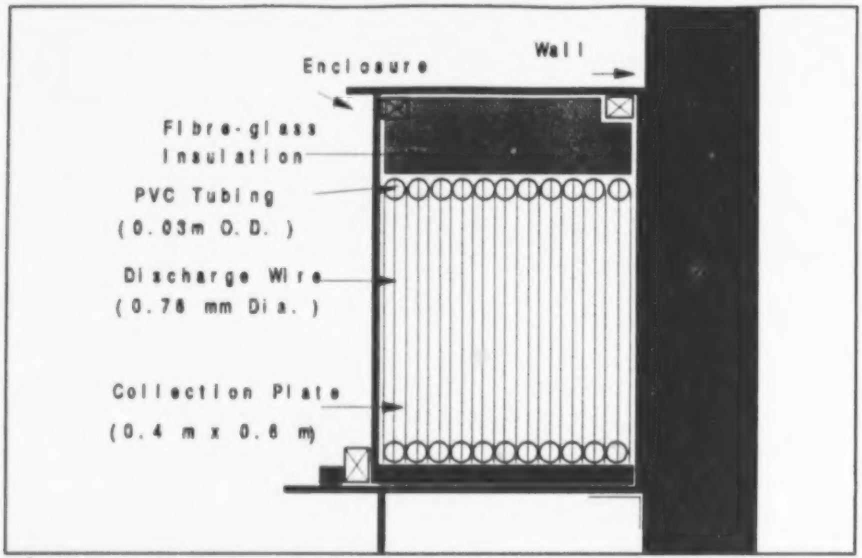
Enclosure
Wall
Fibre-glass Insulation
PVC Tubing
(0.03m O.D.)
Discharge Wire
(0.76 mm Dia.)
Collection Plate
(0.4 m x 0.6 m)

Figure 4.2 A frontal view of the electrostatic precipitator prototype.

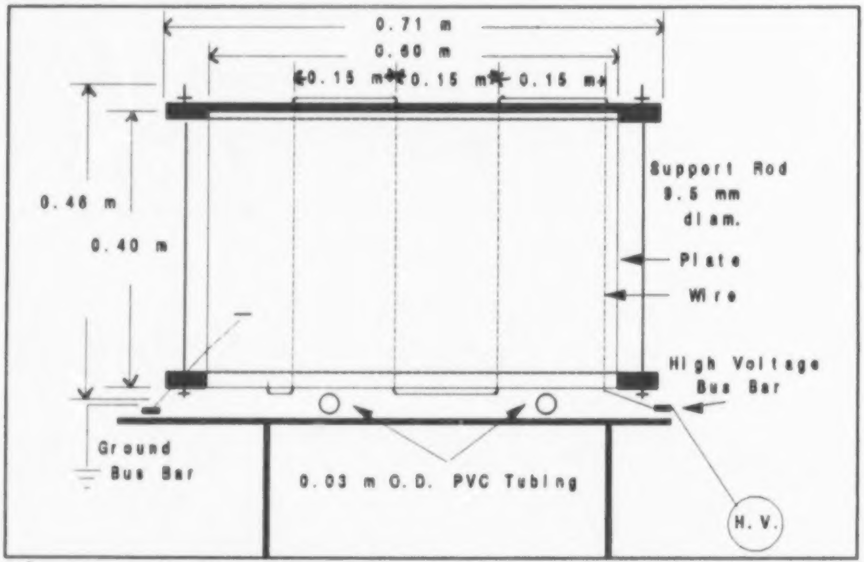
0.71 m
0.60 m
0.15 m
0.15 m
0.15 m
0.46 m
0.40 m
Support Rod
9.5 mm
diam.
Plate
Wire
−
High Voltage
Bus Bar
Ground
Bus Bar
0.03 m O.D. PVC Tubing
H.V.

Figure 4.3 A side view of the electrostatic precipitator prototype without an enclosure.

Excluding the enclosure, the prototype precipitator was 0.71 m long and 0.4 m wide. The discharge wires consisted of approximately a 2.2 m length of stainless steel wire, 0.79 mm in diameter, threaded through the wire frame. One end of the wire length was attached to the high voltage bus bar, while the other end was looped within the frame. The wire was threaded through the frame such that four vertical lengths of wire appear between the collection plates. The four vertical wire lengths in one frame were located 0.15 m apart. The entire unit consisted of eleven wire frames, totalling forty-four discharge wires. The wire frame included two PVC tubing lengths of 0.46 m and 25.4 mm inside diameter, separated by two 0.46 m long steel threaded-rods, 9.5 mm in diameter, one at each length. A discharge wire frame and its four wire lengths is shown in Plate 4-1.

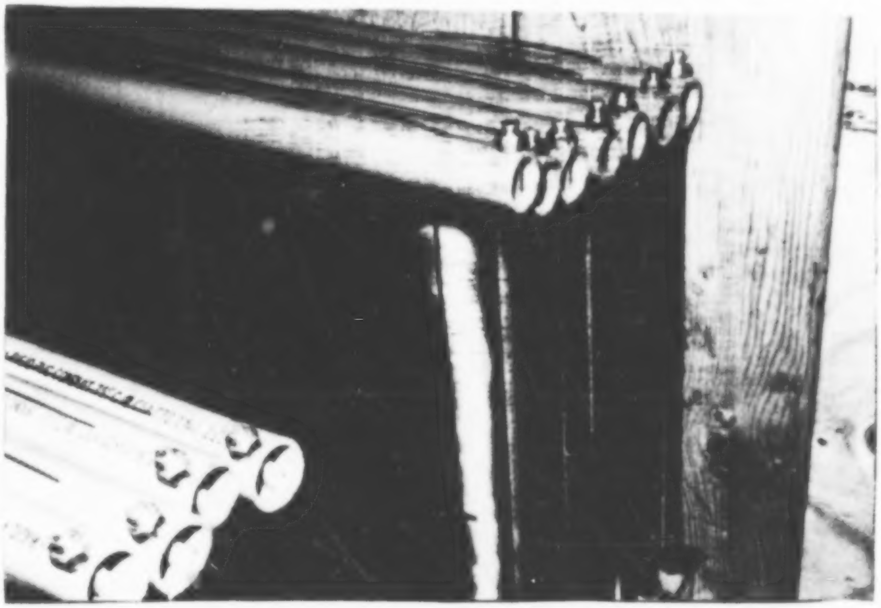

Plate 4-1 A discharge wire frame and collection electrode in the precipitator.

The collection unit consisted of twelve 20-gauge galvanized steel plates, one on each side of the precipitator and between every two wire-frames. The steel plates were 0.60 m long and 0.40 m high, with a thickness of 6 mm. Each of the collection plates were connected to the ground connection on the high voltage power supply via the grounded bus bar. One collection cell, consisted of one discharge wire frame between and including two collection plates. The total number of collection cells within the entire precipitator as shown in Plate 4-2 was eleven, the same as the number of discharge wire frames.

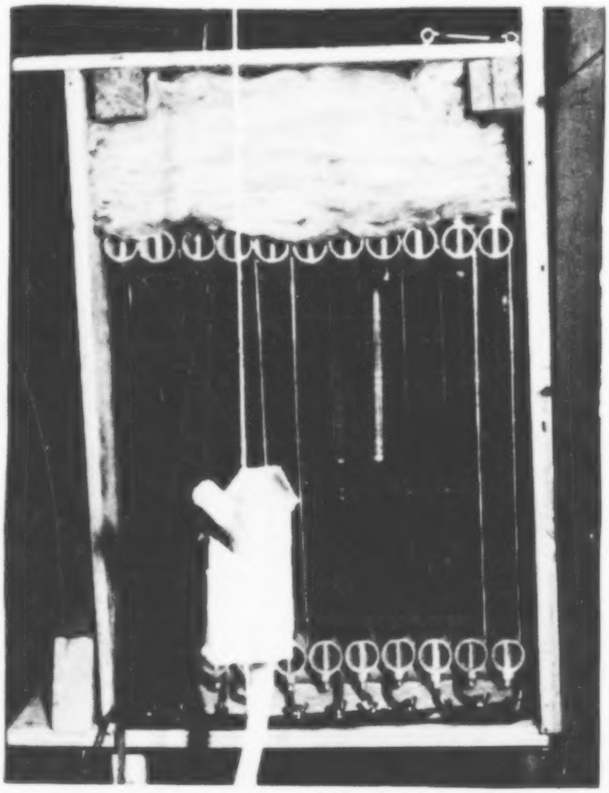

Plate 4-2 A frontal view of the 11 discharge wire frames and 12 collection plates.

The entire air cleaning unit included the electrostatic precipitator, the recirculation fan and duct as shown in the system schematic in Figure 4.4. The precipitator casing consisted of a plywood box tightly holding all the precipitator components together. The casing was removable to enable the manual cleaning of the collection plates. A variable speed, 0.3 m fan, downstream from the precipitator, drew air through the length of the precipitator, then back into the environmental chamber through the recirculation duct. The recirculation duct was 2.8 m long. 0.3 m wide and 0.3 m high and had 12, 0.05 m holes equally spaced along its length.

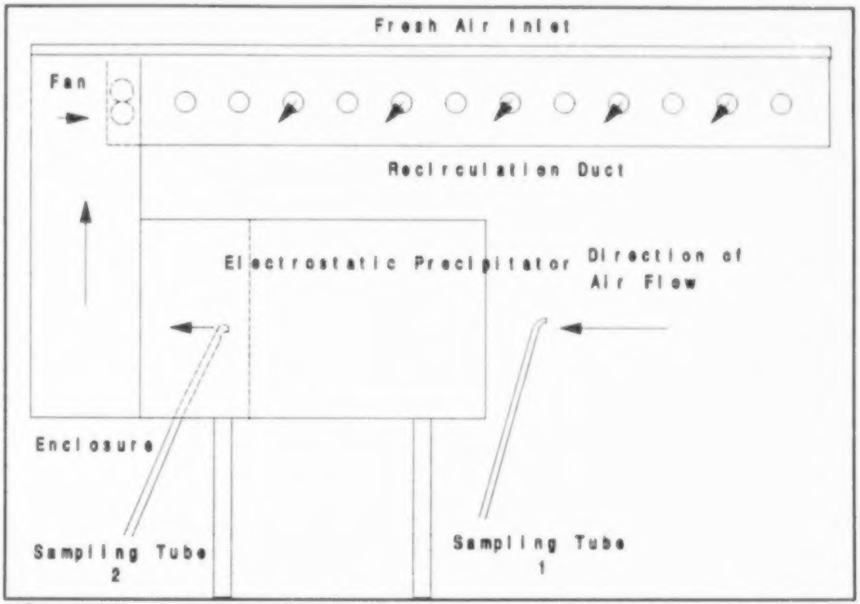
Fresh Air Inlet
Fan
Recirculation Duct
Electrostatic Precipitator
Direction of Air Flow
Enclosure
Sampling Tube 2
Sampling Tube 1

Figure 4.4 A schematic of a total air cleaning system.

4.3 Selected Operating Parameters

Except for design parameters such as precipitator length and plate spacing that could not easily be varied, the other factors which can affect the operation of an electrostatic precipitator are applied voltage and airspeed through the electrostatic precipitator. The three selected levels of applied voltage were dependant upon the characteristics of the power supply when used with the prototype electrostatic precipitator. The high voltage power supply (NJE Corporation, NJ) as shown in Plate 4-3, had the potential to supply 10 mA of current over a 0 to +/-30 kVDC voltage range and was set to supply negative potential with respect to ground.

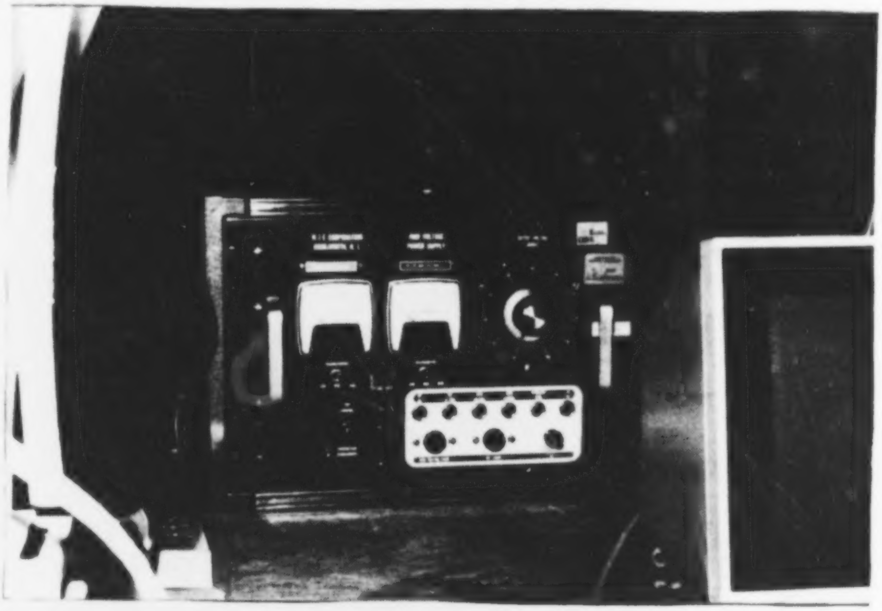

Plate 4-3 A high voltage DC power supply in the outer chamber.

The high voltage power supply had both analog voltage and current displays. Both of these displays were tested against calibrated multimeters. A high voltage probe (Model 80k, Fluke MFG Co. Inc., WA) and multimeter (Model 77, Fluke MFG Co. inc., WA) were constantly connected from the power supply to the high voltage bus bar. The high voltage probe was used to decrease the voltage magnitude by 1000 since the multimeter did not have the capacity to measure high voltages. A multimeter (Model 8060A, Fluke MFG Co. inc., WA), capable of measuring low current was used to calibrate the analog current display.

Although the high voltage power supply was capable of supplying approximately 30 kVDC unloaded, a current drain occurred when it was connected to the prototype. The current drain began occurring at approximately -10 kVDC with the production of corona. As the voltage continued to rise, the corona became stronger as did the production of ozone. The relationship between voltage and current when applied to the prototype in a clean environment is shown in Figure 4.5. The maximum applied voltage at a current of 10 mA was approximately -12.8 kVDC.

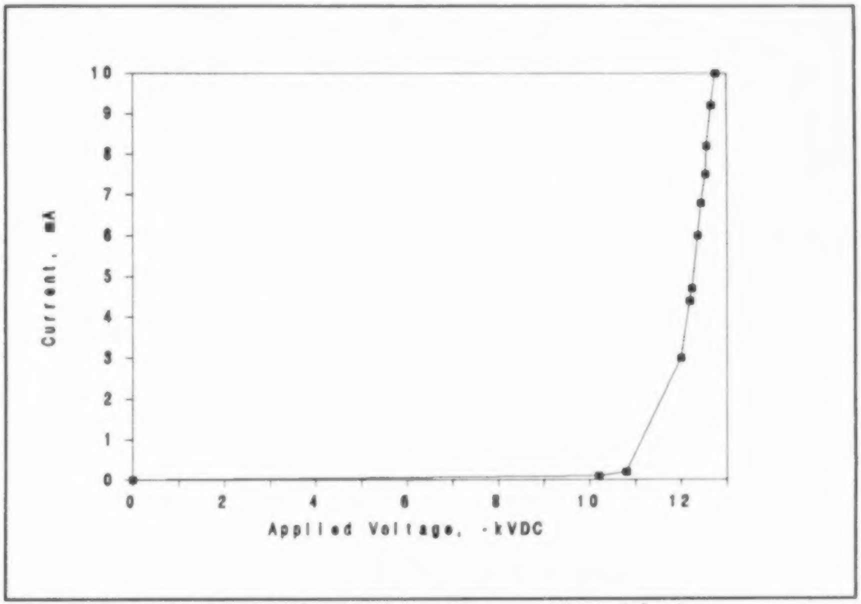

Figure 4.5 Relationship between applied voltage and current flow in the prototype.

The three applied voltage levels selected on a clean precipitator were at: 1)The start of corona discharge; 2)the start of a corona glow upon the wires and 3)a stronger corona glow. Each of these steps was accompanied by a humming sound which represented the corona discharge. At approximately -10.3 kVDC and 0.11 mA, the first level, the humming sound was very low. At the second voltage level, -11.0 kVDC and 0.28 mA, the corona discharge produced approximately one corona tuft per discharge wire with a slightly louder humming noise. At the third voltage level of approximately -12.1 kVDC and 3 mA, many corona tufts were displayed per discharge wire, a much louder humming noise was heard and the production of ozone was detected by odor. Plate 4-4 depicts a corona glow on the last wire to the right of the precipitator as shown by the arrow.

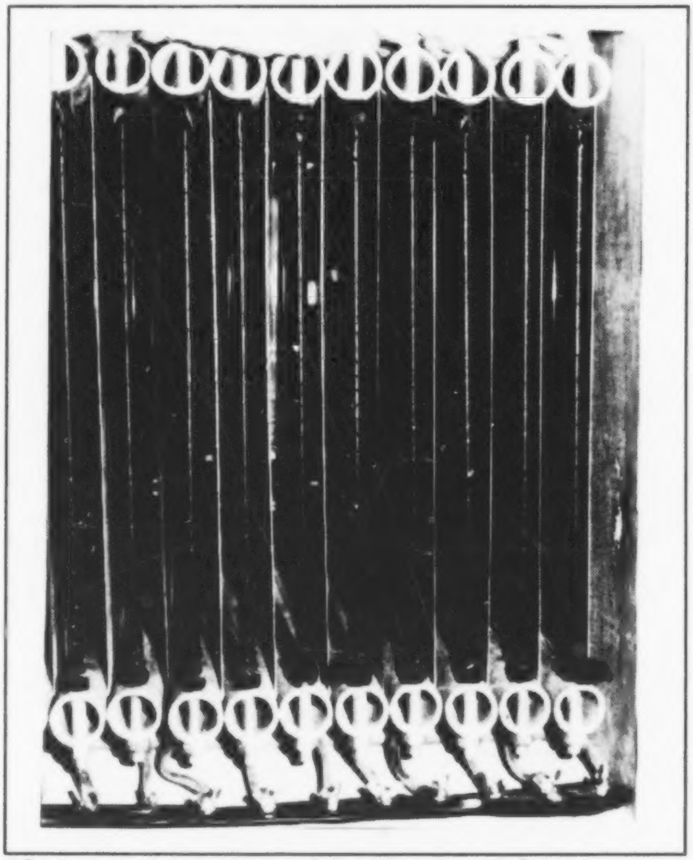

Plate 4-4 Corona glow on one wire.

Rather than adjusting the power supply to deliver the set voltage levels, it was deemed more suitable to set the power supply by current. The current flowing within the precipitator is the factor which produces the corona discharge and is responsible for the dust collection. At approximately a 7°C decrease in inside air temperature, the voltage had to be increased by .3 to .5 kVDC to acquire the similar current produced by a lower voltage at a higher air temperature. This phenomenon was due to the effect of temperature on ionization potential of air as discussed previously. As the air is less dense at a higher temperature and constant pressure, the electrical mobility of the electrons is also higher, producing a corona discharge at a lower voltage.

In industry the recommended current density, or the applied current per unit collection area, is 0.1 - 0.5 mA/(m^2 collection surface) (Matts, 1989). The three voltage levels resulted in current levels of 0.11 mA, 0.28 mA and 3 mA, and current densities of 0.02 mA/m^2, 0.05 mA/m^2 and 0.55 mA/m^2, respectively. The total collection area in the prototype was 5.45 m^2.

The three levels of airspeed, through the electrostatic precipitator were determined by the range capable by the recirculation fan. The airspeed through the electrostatic precipitator was estimated at being represented by the airspeed approximately 0.13 m downstream of the precipitator. The average airspeed throughout the cross-sectional area of the duct at that location was determined by the method described in Appendix B. The air velocity through the duct was measured at 26 locations using a hot-wire anemometer (Velocicalc, Model 8350, TSI Inc., MN). Making the adjustment for an average atmospheric pressure of 93.41 kPa instead of standard atmospheric pressure of 101.3 kPa, the three levels of airspeed selected were: 0.55 m/s, 0.76 m/s and 0.95 m/s.

In summary, the selected applied voltages, currents, airspeeds and their respective levels are as follows:

Level	Voltage kVDC	Current mA	Airspeed m/s
1	-10.3	0.11	0.55
2	-11.0	0.28	0.76
3	-12.1	3.0	0.95

5. EXPERIMENTAL DESIGN

5.1 Testing Equipment

The air cleaning system including the electrostatic precipitator and the recirculation duct were tested within an environmental chamber during the month of May, 1991. The environmental chamber was located at the University of Alberta's Research Station at Ellerslie, Alberta. The interior chamber included the following items:

1) The air cleaning unit (Electrostatic precipitator and recirculation duct);
2) a dust generator (motor, dust hopper, auger, blower and distribution hose);
3) sampling tubes and
4) an exhaust fan.

The interior chamber and the location of the equipment is depicted in Figure 5.1. The dimensions of the chamber are 7.29 m (length), 5.4 m (width) and 1.8 m (height).

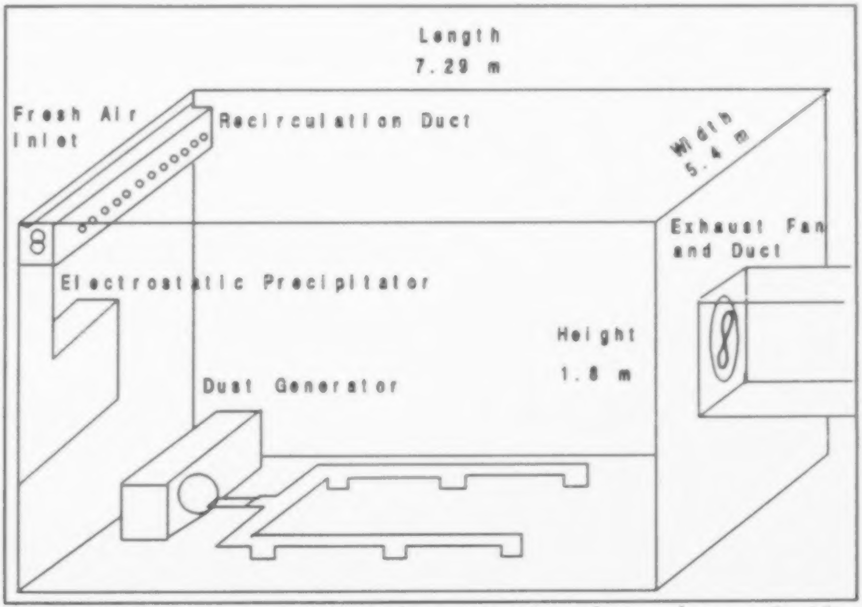
Length
7.29 m
Fresh Air Inlet
Recirculation Duct
Width 5.4 m
Exhaust Fan and Duct
Electrostatic Precipitator
Height
1.8 m
Dust Generator

Figure 5.1 A schematic of the interior of the environmental chamber.

An exterior chamber surrounded the interior chamber and housed the exhaust fan controller and the data sampling aqcuisition equipment including:

1)The sampling tube valve system;
2)an APS particle counter; and
3)a 2 disk-drive Personal Computer.

The high voltage power supply was also kept in the exterior chamber where the current could be monitored. The high voltage and ground leads ran through the wall to connect to the electrostatic precipitator. The sampling tubes also ran through the wall between the interior and exterior chambers.

A mechanical dust generator was used rather than animals to maintain approximate constant dust levels. The swine housing dust used, was collected from the pen floors in a swine finishing unit in Calmar, Alberta. The dust was filtered through a 4.76 mm sieve and then blended by rolling the tubs in which the dust was stored.

Dust Generator

The dust generator depicted in Plate 5-1, included a 6 VAC, 2 A motor, dust hopper, auger, and blower. The motor was used to turn the auger (a spiral wire) to deliver the dust falling by gravity within the hopper, to the blower and subsequently to the distribution tubes. The dust was blown towards the floor or upwards and was picked up by the room air currents produced by the fresh air inlet and recirculation fan. Changing the airspeed through the electrostatic precipitator also affected the airflow from the recirculation duct, therefore the air currents in the room could not be kept constant throughout the experiment.

The aerial dust concentration was one of the items which was to be kept near constant. This was achieved by adjusting the exhaust fan and/or the discharge direction of the tubes.

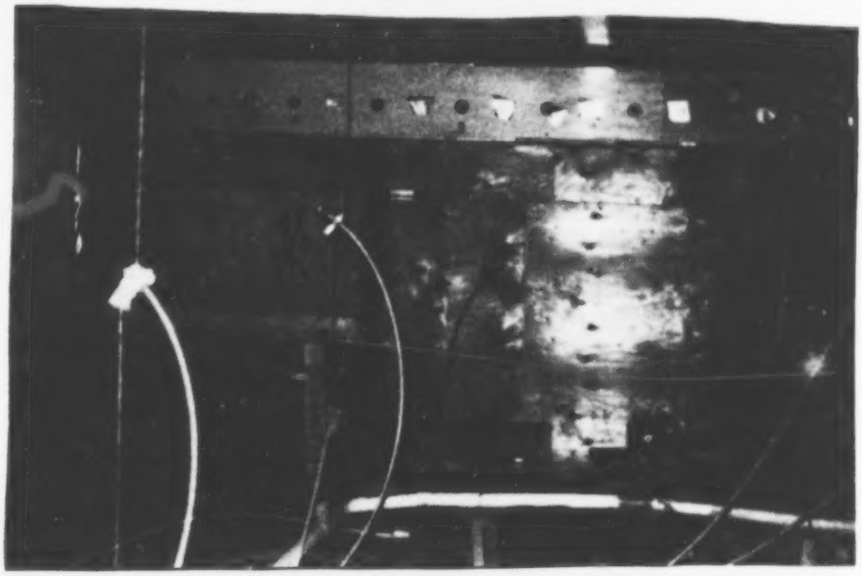

Plate 5-1 The dust generator and the air cleaning system.

Had the exhaust fan speed been kept constant throughout the experiment, aerial dust concentrations would have varied greatly especially between voltage levels 1 and 3 and between airspeed levels 1 and 3. During runs where voltage level 3 was used, the dust collection was much greater than during a run with voltage level 1, therefore the concentration of dust recirculated back into the room was less at voltage level 3. At the low airspeed, the amount of air recirculated back into the room per unit time was less than at a higher speed. Fresh air was also introduced into the room, directly above the recirculation duct allowing for further mixing and dilution of the dust particles.

Sampling Equipment

The sampling equipment included five dust sampling tubes located throughout the room, sampling tube valves a data acquisition interface board (Dascon, Metrabyte Corporation, Taunton, ME) and an aerodynamic particle sizer (APS 3300, TSI Inc. St. Paul, MN). The five sampling locations included: 1)upstream from the electrostatic precipitator; 2)downstream from the electrostatic precipitator; 3)center of the chamber at animal height; 4)center of the chamber at human height and 5)upsteam from the exhaust fan. The sampling tubes consisted of Tygon plastic tubing of 1.3 cm inside diameter.

Each of these five tubes ran from the internal chamber to the external chamber through the wall as shown in Plate 5-2 and connected to the sampling valves as shown in Plate 5-3. The sampling valves each consisted of a motor connected to a rotating ball valve which closed or opened the passage of a sampling tube.

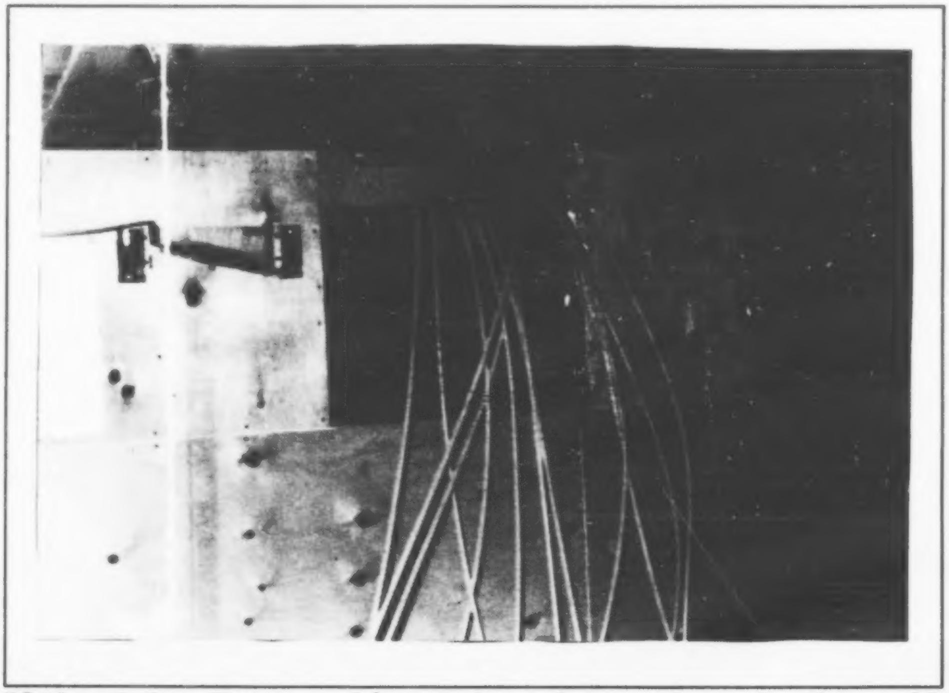

Plate 5-2 The sampling tubes drawn through the wall between chambers.

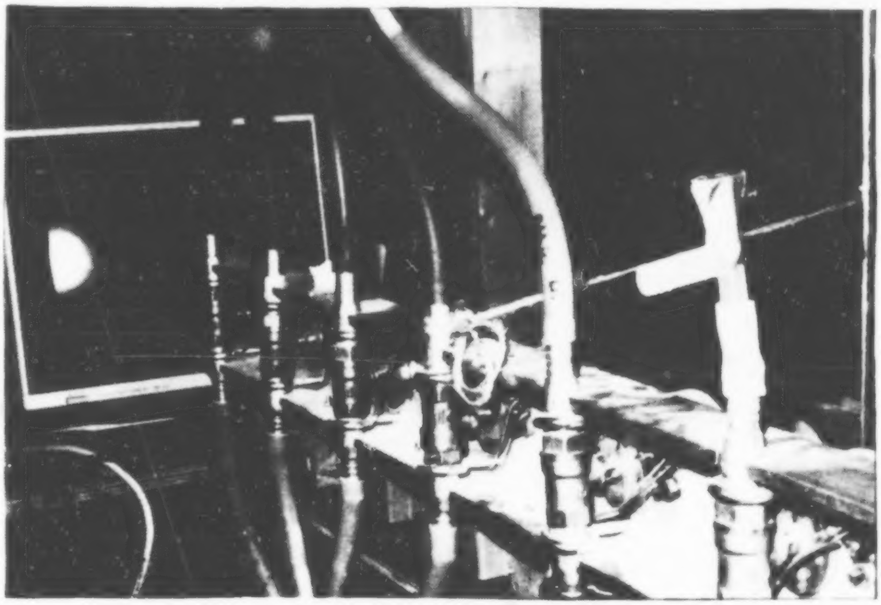

Plate 5-3 The sampling-tube valve system.

The valve motors were actuated by the computer via the data acquisition and control interface board. Although there were only five sampling locations within the internal chamber the sixth valve was used to draw air from the external chamber through the particle counter during an interval period so that a vacuum was not created within the tubing.

A data acquisition run consisted of drawing air from each sampling tube individually for 20 seconds. As one valve was closed the next valve opened. Once one cycle, including a sample for each of the five tubes, had been completed, a rest interval of 1 min. occurred during which fresh air was drawn and no particle counting occurred. This procedure was repeated ten times during one run to produce ten particle counts per sampling location. The approximate duration of a run was 65 minutes.

The main sampling tube from the sampling tube valve system is placed in the opening of the particle counter. The APS measured particle aerodynamic diameters in real-time. In the APS, the particle-laden air is passed through a thin-walled orifice. Because of their higher inertia, the particles lag behind the air, with the velocity lag being representative of the aerodynamic diameter of the particle. The aerodynamic diameter can be measured by measuring the velocity of the particle as it exits from the orifice.

To measure the particle velocity, a laser beam is split in two and these are focused into two rectangular spots in front of the orifice. The light scattered by a particle passing through these beams is collected into the photomultiplier tube (PMT). The PMT emits two pulses separated by the time taken by the particle to cross the distance between the two slits. The aerodynamic diameter of the particle is calculated using the time the particle took to pass between the two slits.

Prior to performing the experiment, the APS was calibrated with known particles of uniform latex polystyrene microspheres (0.496, 0.966 and 2.01 μm), Styrene-Vinyltoluene Latex Polymer Microspheres (2.96 μm), and Polymer Microspheres (3.983, 9.870 μm) (Duck Scientific Corp., Palo Alto, CA). The calibration identified the bins on the APS interface board associated with a specific particle size. This calibration information was included in the BASICA program used to control the particle sampling and data storage on 5 1/4" floppy diskettes in the IBM XT Personal Computer. The BASICA program is included in Appendix C.

5.2 Experimental Design

The experimental approach was based upon a split-plot factorial experimental design so that the resulting dust concentration data could be analysed using a general linear model procedure. The two independent factors, applied voltage and airspeed through the precipitator, each had three levels and when combined yielded a possible nine test combinations. Each of these combinations had three replicates which were performed randomly resulting in a total of twenty-seven runs. The statistical model of the experiment was:

$$C = \mu+V_i+S_j+VS_{ij}+R_{k(ij)}+D_\ell+DV_{i\ell}+DS_{j\ell}+VSD_{ij\ell}+DR_{k\ell(ij)} \qquad (5\text{-}1)$$

where: C = collection efficiency,
μ = overall mean,
V_i = applied voltage level, $i=1,2,3$
S_j = airspeed level, $j=1,2,3$
R_k = replicates, and $k=1,2,3$
D_ℓ = samples per run. $l=1,2,3...10$

5.3 Experimental Methods

Measurements

In addition to particle sampling, several other measurements were performed during each run. These included: 1)measuring the initial and final dry and wet-bulb temperatures; 2)measuring the ozone concentrations; 3)collecting dust samples from the front and rear of a collection plate; 4)recording the voltage and current within the precipitator for each of the ten samples per run and 5)measuring the exhaust fan speed during each of the ten samples per run.

The initial and final dry and wet-bulb temperatures were measured using a sling psychrometer (Model 1328A, Taylor Inc., USA). These values were used to find the average air temperature and relative humidity within the chamber during a run.

The O_3 measurements were made using a Matheson-Kitagawa

Toxic Gas Detector (Model 8014-400A, Matheson Safety Products, E. Rutherford, NJ). The tubes (Model 182U Ozone, Matheson Safety Products,E. Rutherford, NJ) used in conjunction with the gas detector were capable of detecting gas ranges within the range of 0.05 to 3.0 ppm. Corrections were not required for the temperatures and relative humidities encountered during the experiment. Ozone concentrations were measured for only nine of the total twenty-seven runs. Each of these nine runs were selected randomly and represent each of the nine voltage - airspeed combinations. The measurements were taken directly upstream from the electrostatic precipitator inlet since this was nearest the location where the ozone was being produced.

The collection of a dust sample from the collection plates was similar to the ozone measurements such that a sample was taken for each of the nine voltage - airspeed combinations. The runs in which this was performed were also selected randomly. A sample of dust was scraped from the collection plate into a plastic bag using a sharp blade. Dust from the two center plates was always used to best represent the dust flowing throughout the entire precipitator. A sample from the front of the plate, adjacent to the first wire and a sample from the rear of the plate, adjacent to the fourth wire were each collected in separate bags. This sampling was performed to determine whether the particle sizes and constituents collected varied along the length of the collection plate. The dust analysis was performed using a scanning electron microscope (Department of Entomology, University of Alberta).

The voltage and current were recorded manually throughout the run to determine average voltage and current levels. These values were also an indication of whether the precipitator was operating properly. The voltage was measured using a Fluke 77 multimeter while the current was read directly off the high voltage power supply scale. In certain instances, especially towards the end of a level three voltage run, the current within the precipitator had a tendency to increase due to an increase in electric field. If the current was left to increase, sparking would eventually occur, shutting down the high voltage power supply as well as stopping the computer program. Since this disturbance was undesirable, the current was controlled by decreasing the voltage as it approached the sparkover level. Basically, the current and applied voltage varied little within a run and were allowed to fluctuate slightly, due to the natural corona changes occurring with time in the electrostatic precipitator.

The 0.64 m diameter, 7-blade propellor exhaust fan (Model 562-2, Ziehl-Abegg Co.) as depicted in Plate 5-4 was located opposite the air cleaning unit.

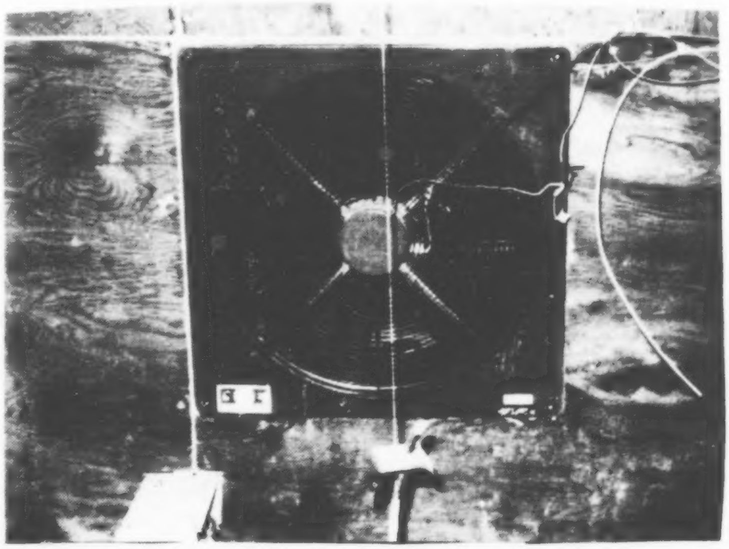

Plate 5-4 The exhaust fan in the interior chamber.

The fan speed was varied using a 4.5A 120 VAC Controller (Model WM-14M, TriVar Inc., Mississauga, ON). The exhaust fan speed was measured in the 0.25 m^2 duct located downstream from the fan, extending outside of the chamber. The air velocity based on a 25-point profile in accordance with Jorgenson (1983). This measured airspeed, when multiplied by 0.88 represented that at the centre of the exhaust duct. This value of 0.88 also included the correction for atmospheric pressure. The resulting airspeed represented the mean airspeed through the entire cross-section of the duct.

The exhaust speed was reduced if the dust concentrations within the room were decreasing too quickly during the run. Similarly, the exhaust speed was increased if the dust concentrations were exceeding required dust levels. Desired dust concentrations within the room, especially upstream from the electrostatic precipitator were 20 to 70 particles/mL to represent typical conditions within a swine barn. The distribution tubes through which the dust entered the chamber could be turned upwards to quickly increase the aerial dust concentrations. Therefore, the only methods to control dust levels within the chamber during a run were to vary the exhaust fan speed and change the direction of the distribution tubes.

Experimental Procedure

The general procedure followed during each run throughout the experiment included the following steps:

1. Preliminary measurements and settings
   - 1.1 turn APS particle counter on (required 20 minutes to warm up);
   - 1.2 clean sampling tubes with compressed air;
   - 1.3 measure wet and dry-bulb temperatures;
   - 1.4 fill dust generator hopper;

  - 1.5 turn exhaust fan on;
  - 1.6 set recirculation fan at required speed level;
  - 1.7 set voltage level, and
  - 1.8 start sampling program.

2. Measurements during run
  - 2.1 during every rest interval, every five minutes record exhaust fan speed, applied voltage and current;
  - 2.2 monitor the dust concentrations throughout the room to maintain consistency, and adjust exhaust speed if required.

3. Post run measurements and activities
  - 3.1 measure ozone concentrations just upstream from the precipitator if necessary;
  - 3.2 measure wet and dry bulb temperatures;
  - 3.3 turn the power supply and recirculation fan off;
  - 3.4 take dust samples off the collection plates if necessary;
  - 3.5 clean the discharge and collection electrodes, and
  - 3.6 sweep the environmental chamber and prepare for next run.

Summary of Settings

The only instrument settings which were held constant throughout the experiment were the APS particle counter settings and include: 1)Total flow at 3.875 V; 2)pressure drop at 2.9 V and 3)the sheath flow at 3.547 V. These voltage levels represent the actual airflow passing through the counter and can indicate plugging or other problems if large variations occur during a run. These settings were taken from the APS manual and correspond to the air flow of 16.67 mL/s (APS, TSI Inc. St. Paul MN).

The precipitator voltage levels were approximately -10.3 kVDC (0.11 mA), -11.0 kVDC (0.28mA) and -12.1 kVDC (3 mA). The airspeed levels through the electrostatic precipitator were 0.55 m/s, 0.76 m/s and 0.95 m/s. These airspeeds were measured once and throughout the experiment the recirculation fan controller was set at the required setting to provide the desired speeds. The airflows through the exhaust fan varied from a minimum of 976 m^3/h (271 L/s) to a maximum of 4602 m^3/h (1278 L/s).

6. RESULTS

6.1 General Observations

Throughout the remainder of this report applied voltage levels 1, 2 and 3 will represent applied voltages of -10.3, -11.0 and -12.1 kVDC, respectively. Airspeed levels 1, 2 and 3 will represent airspeeds through the precipitator of 0.55, 0.76 and 0.95 m/s.

Observing the variation in dust collection between different runs is important in understanding the method of electrostatic precipitation. At the end of each run, regardless of applied voltage, a very thin layer of dust which

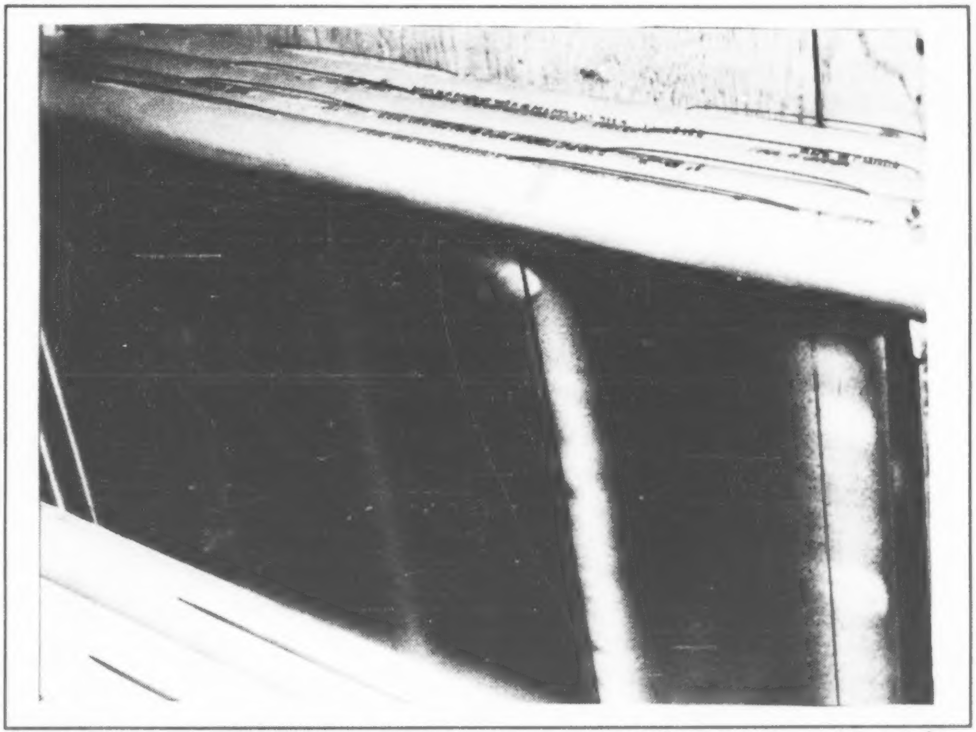

Plate 6-1 Pattern of dust collection on collection electrode in precipitator for an applied voltage of -12100 VDC (3 mA).

had accumulated upon the entire plate with the main dust accumulation occurring in four strips in the immediate vicinity of the discharge wires. Plate 6-1 depicts the fifth wire frame and collection plate within the electrostatic precipitator. The photo was taken after a run of applied voltage of -12.1 kVDC at an airspeed of 0.55 m/s. Observations made from this view of the discharge wires and collection plate, included:

1) The discharge wire nearest to the inlet had the most accumulation of dust upon its surface except in the areas of corona discharge;
2) the dust seemed to collect in a shape representing the actual corona discharge occurring around the wires;
3) streaks of dust appeared on the collection plate near the part of the wire where there was the least amount of dust upon the wires, signifying a stronger corona at these regions, and
4) towards the end of the collection plate, the collected dust layer appeared thinner and more even, than the layer near the front of the plate.

Usually after a 1-h run the dust collected upon the plates was even, especially at higher airspeeds and higher dust concentrations. The dust collection upon each of the 12 collection plates was similar, implying that the airflow and dust loading was evenly distributed along the width and height of the precipitator. There were two discharge wire frames which supported slightly bent wires. The two wires each bent slightly towards a collection plate and severe corrosion upon these collection plates occurred over the 27 runs. The corrosion of one of these plates is shown in Plate 6-2.

Plate 6-2 shows a slight dust layer at four locations upon the plate, however under the dust an imprint of the corona outline can be seen. The imprint took the shape of little tufts that were produced by the corona. Since this occurred upon only two plates, it was assumed that it was due to the slight bow of the wires or collection plates.

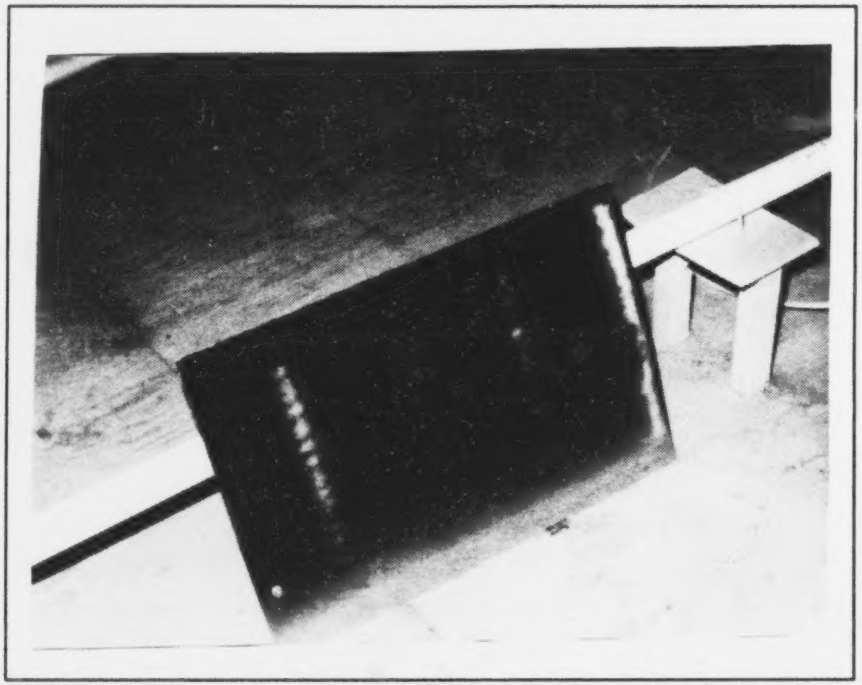

Plate 6-2 A collection plate showing some corrosion beneath the dust layer.

The collected dust layers appeared slightly different between the applied voltage levels. As shown previously, the dust accumulated in a series of tufts parallel to the length of the wire at the applied voltage of -12.1 kVDC. As the corona current decreased with decreasing applied voltage so did the appearance of the tufts surrounding the wires. With a decrease in the number of tufts, the dust tended to accumulate in a smoother pattern parallel to the discharge wires with no spikes.

6.2 Environmental Conditions

The average dry-bulb temperature within the environmental chamber throughout the experimental runs was 21°C, with a minimum and maximum temperature of 14°C and 26.5°C, respectively. The average relative humidity within the chamber varied between the minimum and maximum values of 33 and 64%, respectively with an average of 50% RH.

Since the experiment was performed during three weeks in May, the outside environmental conditions did not vary greatly during the experiment. The minimum and maximum atmospheric pressures measured at the International Airport south of Edmonton for the month of May were 91.7 and 94.5 kPa, respectively. The average atmospheric pressure, P_{atm}, to be used in subsequent calculations is 93.4 kPa. The pressure correction factor, F, to be used for the air speed and ozone measurements is equal to the ratio of sea-level P_{atm} to the actual P_{atm} in Edmonton. The value of F is 1.08 and will be used in subsequent sections.

6.3 Particle Size Distribution

The APS particle counter and its interface boards were programmed such that the particle counts were made for the following 17 size ranges: $d< 0.5\mu m$; $0.5\mu m <d< 1\mu m$; $1\mu m <d< 2\mu m$; $2\ \mu m <d< 3\mu m$; $3\mu m <d< 4\mu m$; $4\mu m <d< 5\mu m$; $5\mu m <d< 6\mu m$; $6\mu m <d< 7\mu m$; $7\mu m <d< 8\mu m$; $8\mu m <d< 9\mu m$; $9\mu m <d< 10\mu m$; $10\mu m <d< 11\mu m$; $11\mu m <d< 12\mu m$; $12\mu m <d< 13\mu m$; $13\mu m <d< 14\mu m$; $14\mu m <d< 15\mu m$; and $d> 15\mu m$. Therefore, for each run including 10 samples at each of the five sampling locations, 850 dust concentrations were recorded. The particle counts per unit time, calculated by the APS particle counter were divided by the airflow through the particle counter of 16.67 mL/s, to produce a dust concentration of particles/mL. The raw data are included on a diskette in the Appendices.

The first two locations, upstream and downstream from the electrostatic precipitator were the important sampling locations for analysis purposes. The other sampling locations were used to monitor any problems which might have occurred, either with insufficient airflows or the plugging of the dust generator and tubes. These locations were monitored so that a fairly constant dust concentration between 20 to 70 particles/mL was present in the environmental chamber.

Eventhough 17 particle size categories were selected, the first 9 size categories ranging from less than 0.5 μm to 8 μm were those that were used in the analyses. There were very few incidences of any particles being greater than 8 μm. The size distribution was determined for the average dust concentrations measured for the ten samples of each of the 27 runs. The incremental and cumulative particle size distributions are shown in Figure 6.1. The data from which the plot in Figure 6.1 is derived are given in Table 6-1.

Table 6-1 Particle size distribution data for swine dust.

Diameter range, μm	Average diameter, μm	part /mL	$n(d_p)$ /N	$N(d_p)$ /N
<0.5	0.25	4.4	0.108	0.108
0.5-1.0	0.75	4.18	0.103	0.212
1.0-2.0	1.5	16.4	0.404	0.615
2.0-3.0	2.5	9.7	0.239	0.855
3.0-4.0	3.5	3.79	0.093	0.948
4.0-5.0	4.5	1.37	0.034	0.982
5.0-6.0	5.5	0.44	0.011	0.993
6.0-7.0	6.5	0.15	0.004	0.996
7.0-8.0	7.5	0.14	0.003	1.00
Total		40.6		

The size distribution as shown in Figure 6.1 was determined for the dust present directly upstream from the electrostatic precipitator. The average total number of particles upstream from the electrostatic precipitator inlet was 40.6 particles/mL. The median, modal and mean particle diameters were 1.7 μm, 1.5 μm and 1.9 μm, respectively. The calculations for these data are included in Appendix D.

The median diameter means that 50% of the total number of particles is greater or less than 1.7 μm. The modal diameter, 1.5 μm, is that diameter at which the greatest number of particles occur. The mean diameter represents the arithmetic average diameter of all the particles. The mean particle diameter is the diameter at which the curves representing n(dp)/N and N(dp)/N intersect. It should be noted that each of these parameters has a different scale on the size distribution curve.

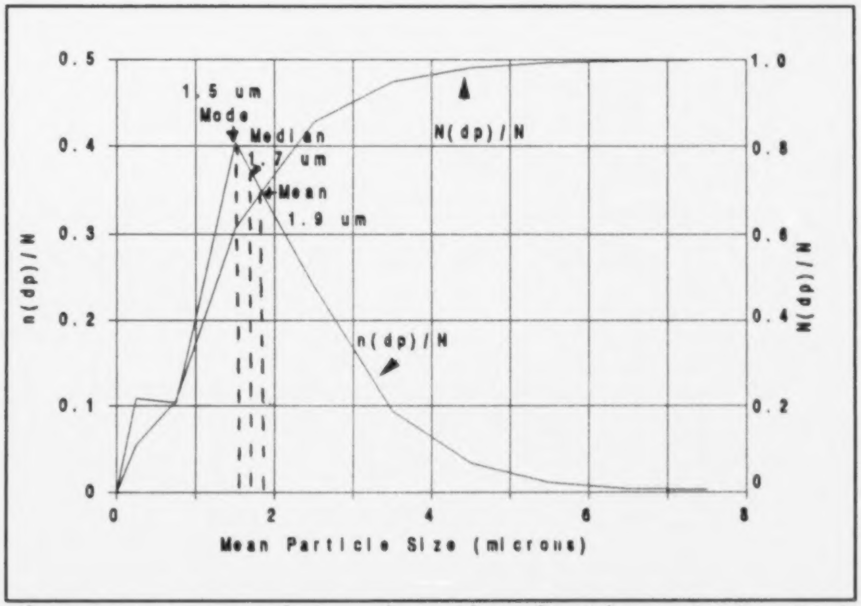

Figure 6.1 Particle size distribution of the dust used in the experiment.

6.4 Microscopic Identification

The two dust samples taken from each of the voltage - airspeed combinations were labelled front and rear corresponding to their location on the collection plate from which they were removed. Fourteen of the total 18 particle samples were analysed using a scanning electron microscope. The particle constituents and their sizes were identified for each sample and are tabulated in Table 6-2. The particle sizes and constituents identified for each sample are compared based upon the location on the collection plate (front or rear) and whether they were fecal or starch particles. The numbers in brackets represent the number of fecal particles within a sample. The numbers outside the brackets represent the number of starch particles within a sample.

Table 6-2 Microscopic observation of particles collected.

Voltage kVDC	Air-speed m/s	front,f rear,r	d<5 μm particles	5<d<10μm particles	d>10μm particle
-10.2	0.55	f	2 (24)	5 (7)	11 (6)
		r	1 (6)	6 (11)	2 (5)
-10.3	0.76	f	0 (15)	0 (7)	1 (2)
		r	0 (13)	3 (8)	1 (6)
-10.2	0.95	f	1 (13)	2 (5)	7 (5)
		r	0 (12)	2 (1)	0 (3)
-11.1	0.55	f	1 (8)	0 (1)	1 (3)
		r	0 (17)	3 (2)	0 (2)
-11.1	0.76	f	0 (12)	3 (3)	3 (8)
		r	0 (5)	1 (3)	0 (0)
-10.9	0.95	f	2 (15)	3 (7)	9 (8)
		r	0 (10)	0 (1)	1 (1)
-12.0	0.55	f	0 (29)	1 (3)	10 (7)
		r	0 (7)	3 (1)	1 (10)

( ) - fecal particles, other values are starch particles

Generally the types of constituents that were identified included: starch, fecal material, skin, plant hair, minerals (K, Cu) and bran. The particles identified in the highest proportions were starch and fecal. The fecal particles were the main constituents less than 5 μm. The plant hairs could have been from the feed whereas the bran could have been part of the fecal material.

A large number of particles were identified as being greater than 10 μm in diameter. This was not found from the data accumulated by the APS particle counter, which could be due to a difference in calibration or accuracy between the APS and the SE microscope. Cohesion is an important method by which collected dust remains upon the collection plate even after the power supply has been turned off, therefore the particles analysed by the SEM could have been several particles held together through electrostatic forces, thus increasing their size.

Two dust samples representing the dust collected at the front and rear of the plate during a run of applied voltage level 2 and airspeed level 2, were photographed. The micrographs of the dust collected on the front and rear sections of the collection plate are shown in Plates 6-3 and 6-4.

The small circular particles are starch particles. The long thin strands were identified as being plant hairs. It should be noted that there are several particles agglomerated together forming a clod of particles. The main constituents less than 5 μm in these samples were fecal particles. From the micrographs the main differences observed between the front and rear of the plate were: 1)a higher ratio of larger non-respirable particles to smaller particles collected at the back, and 2)many more particles were identified in the front area of the plate.

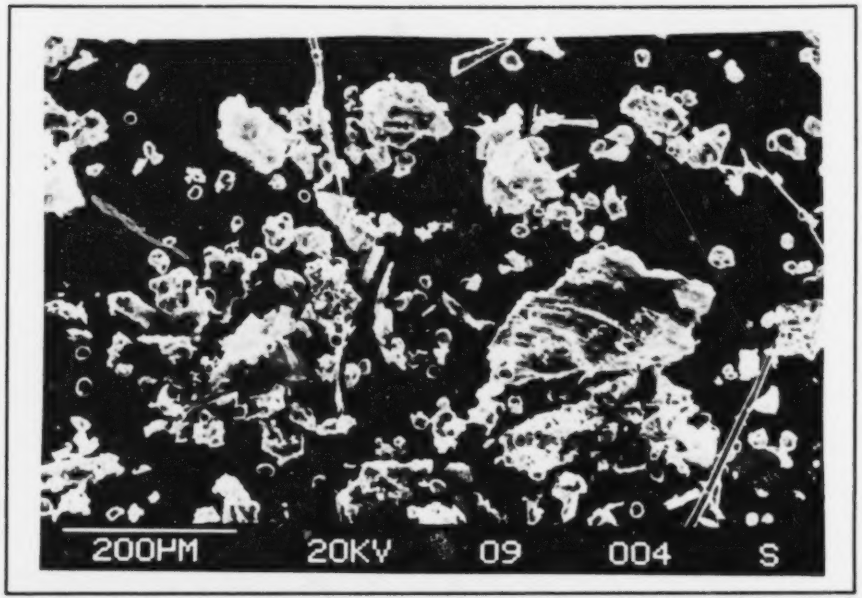
200µM
20KV
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Plate 6-3 A SEM micrograph of the dust collected near the inlet of the precipitator at a voltage of -11.1 kVDC.

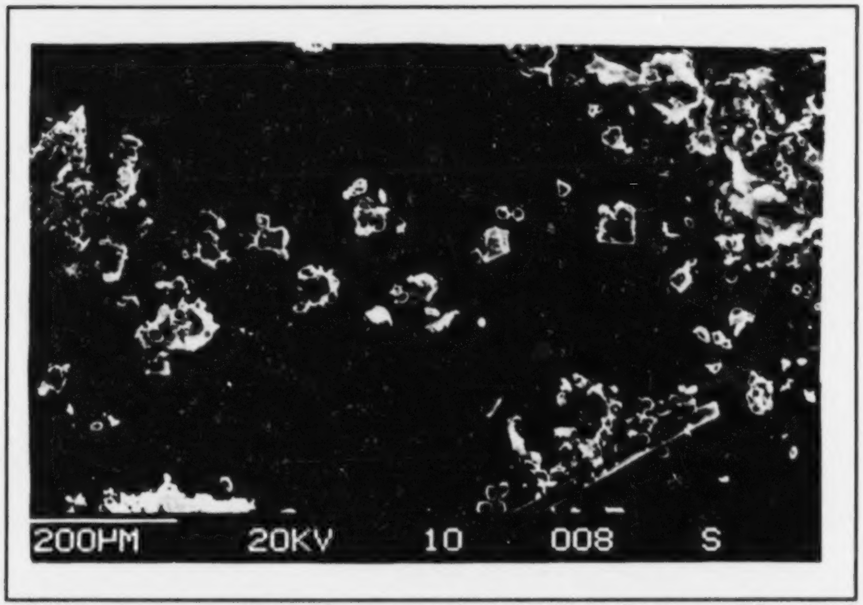
200µM
20KV
10
008
S

Plate 6-4 A SEM micrograph of the dust collected near the precipitator outlet at a voltage of -11.1 kVDC.

6.5 Overall Collection Efficiency

As discussed earlier, dust concentrations were accumulated by the APS particle counter, for various particle size ranges. Using a BASICA program the collection efficiencies were calculated for each sample within a run using equation 2-1, for the different particle size ranges.

$$\eta_d = 100 \cdot (1 - B \cdot A^{-1}) \tag{2-1}$$

where: η_d = collection efficiency for size range d, %,
A = number of particles upstream, part./mL, and
B = number of particles downstream, part./mL.

The individual collection efficiencies were calculated using the particle counts upstream and downstream from the electrostatic precipitator. The sampling tubes were located such that the dust sampled was representative of the dust entering or leaving the precipitator.

The collection efficiency ratio represented the number of particles collected to the number of particles entering the electrostatic precipitator. For each voltage - airspeed combination, the result of collection efficiency times the number of particles were summed over the nine particle size ranges.

The equation used for the overall collection efficiency which represents the collection of all particle sizes is given in equation 2-2. The data for the overall collection efficiency calculations are given in Appendix J, and a sample calculation is included in Appendix E.

$$\eta_o = \Sigma(n_d \cdot \eta_d) \cdot (\Sigma(n_d))^{-1} \tag{2-2}$$

where: η_o = Overall collection efficiency, %
n_d = particle concentration at size d, part./mL, and
η_d = collection efficiency at size d, %.

6.5.1 Effect of applied voltage

The overall collection efficiency η_o, ranged from a minimum of 18.6% at voltage level 1 and airspeed of level 3 to a maximum of 96.4% at voltage level 3 and airspeed level 1.

η_o is plotted against airspeeds in Figure 6.2. Referring to this figure, the applied voltage level 3 yielded the greatest values for η_o, as applied voltage level 1 yielded the lowest values for η_o.

For applied voltage level 1, η_o was 37.8%, 27.7% and 18.6% for the airspeed levels 1, 2 and 3, respectively. For applied voltage level 2, η_o was 44.7%, 46.6%, and 47.5% for the airspeed levels 1, 2 and 3, respectively. For applied voltage level 3, η_o was 96.4%, 91.1% and 91.1% for the airspeed levels 1, 2 and 3, respectively.

Generally, the collection efficiencies for each voltage level decreased with increasing airspeed. The exception was for the medium applied voltage at which the collection efficiency increased slightly with airspeed.

6.5.2 Effect of airspeed

The results plotted in Figure 6.2 against airspeed are also plotted in Figure 6.3 against applied voltage. In summary, the lowest airspeed produced the highest overall collection efficiencies at the applied voltage levels 1 and 3.

The exception as was discussed previously, was the value for η_o at airspeed level 3, which was slightly greater at applied voltage level 2.

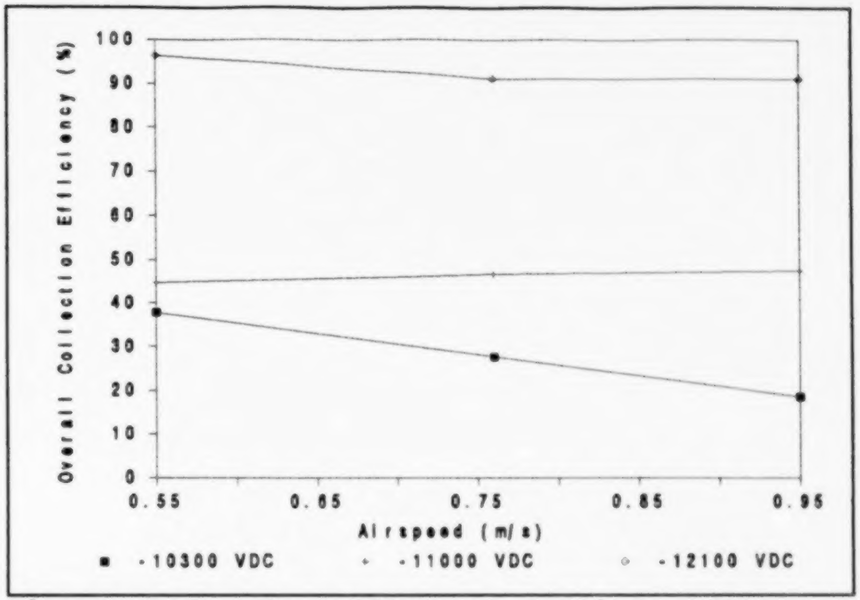

Figure 6.2 The effect of applied voltage on overall collection efficiency.

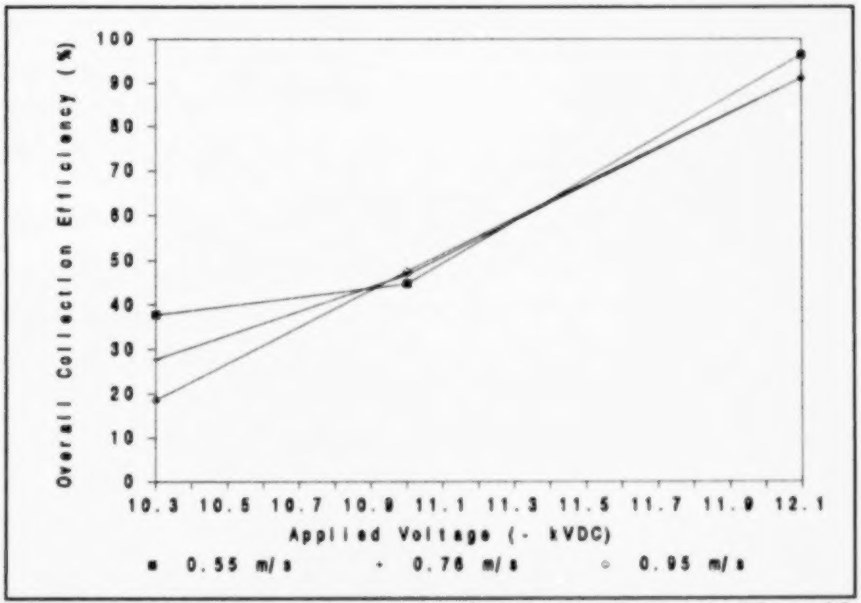

Figure 6.3 The effect of airspeed on overall collection efficiency.

6.5.3 Statistical analysis

The values for overall collection efficiency were analysed using the Statistical Package, SAS version 6.0, to determine the effect of voltage and airspeed. The mean values calculated in the analysis were the same values plotted in Figures 6.2 and 6.3 and were also used in subsequent calculations. The standard error mean for the results was 5.13.

The conclusions from the statistical analysis included: 1)Applied voltage had a significant effect upon overall collection efficiency ($P < 0.05$); 2)the airspeed through the electrostatic precipitator did not have a significant effect upon overall collection efficiency ($P < 0.05$), and 3)the interaction between airspeed and applied voltage was not significant ($P < 0.05$). The statistical results are given in the General Linear Models Table in Appendix E.

6.5.4 Standardization of airflows for particle concentration

The difference in airspeeds as well as the particle concentration upstream from the electrostatic precipitator, resulted in a difference of the number of particles passing through the electrostatic precipitator per unit time.

An equivalence factor which represents the airflow through the precipitator multiplied by the particle concentration, was used to eliminate the factor of varying particle concentrations and airflows.

The factored efficiency is the product of the overall efficiency (η_o), the airflow (Q) and the total particle concentration (Nt) upstream from the precipitator. The factored efficiencies are plotted in Figures 6.4 and 6.5 against airspeeds and applied voltages, respectively.

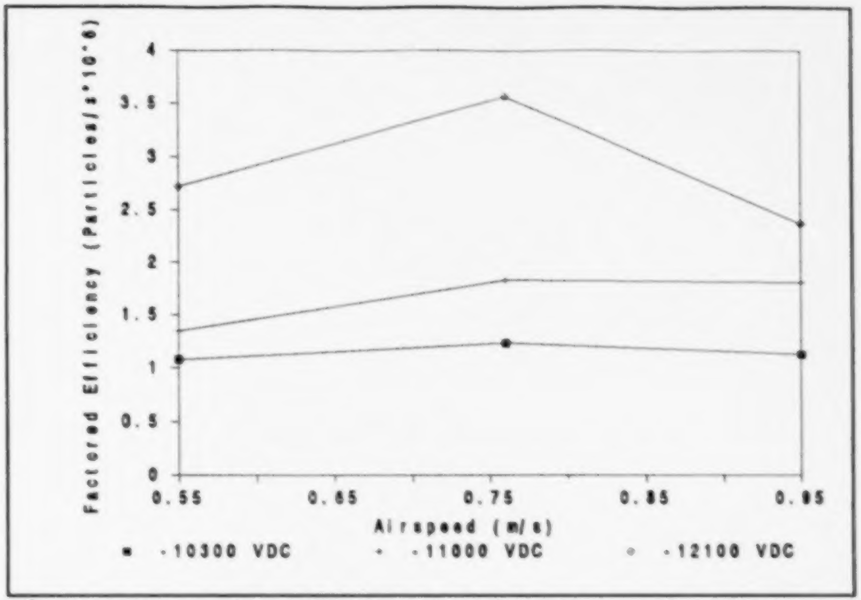

Figure 6.4 The effect of voltage on the factored collection efficiencies.

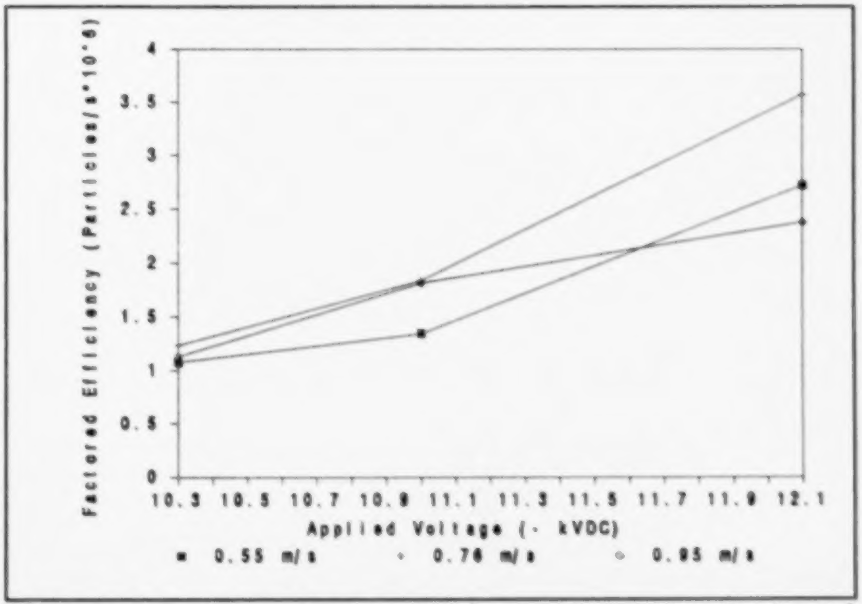

Figure 6.5 The effect of airspeed on the factored collection efficiencies.

The three airflows through the electrostatic precipitator were a result of the three airspeeds multiplied by the specific cross sectional area of the electrostatic precipitator (0.12 m^2).

The units of the factored efficiency values are particles·10^6/s. These values are not significant in themselves. However when compared to the variable factors of airspeed and voltage, they may result in different trends from those in Figures 6.2 and 6.3. Generally, the highest factored efficiency determines the optimal voltage, airspeed level or voltage - airspeed combination. The trends shown in Figure 6.2 as compared to Figure 6.4 are similar. However, some differences were noted between the airspeeds. The highest factored and overall collection efficiencies were achieved at applied voltage level 3 for every airspeed.

Figure 6.3 shows that the highest collection efficiencies at voltage levels 1 and 3 were achieved at airspeed level 1. However, in Figure 6.5 the optimal airspeed of 0.76 m/s at level 2, yielded the highest factored efficiencies at each voltage level. The aforementioned results as given in Table 6-3 include: the overall and factored collection efficiencies, the particle number concentration at the inlet of the precipitator, the applied voltages and currents and the airspeeds.

Table 6-3 The summary of overall and factored collection efficiencies.

Applied Voltage kVDC	Cur-rent mA	Air-Speed m/s	T_{db} °C	RH %	η_o %	Nt part/mL	η_oQNt (part $*10^6$ /s)
-10.2	0.15	0.55	23.4	45	37.8	41.9	1.08
-10.3	0.08	0.76	20.6	47	27.7	47.4	1.23

-10.2	0.14	0.95	22.2	43	18.6	51.8	1.13
-11.1	0.25	0.55	23.7	46	44.7	44.2	1.34
-11.1	0.31	0.76	19.4	53	46.6	41.9	1.83
-10.9	0.26	0.95	23.3	48	47.5	32.5	1.81
-12.0	3.18	0.55	19.8	56	96.4	41.5	2.72
-12.1	3.19	0.76	19.6	55	91.1	41.7	3.57
-12.2	2.89	0.95	16.3	53	91.1	22.3	2.38

6.5.5 The Deutsch-Anderson Relationship

The Deutsch-Anderson relationship in Equation 2-11, relates the collection efficiency to the air velocity, precipitator length, inter-electrode spacing and the effective migration velocity. Using the original and the modified Deutsch-Anderson relationships, the original and modified effective migration velocities, $\tilde{\omega}$ and $\tilde{\omega}_k$ were calculated. Since the modified Deutsch-Anderson relationship was based upon the assumption that the average migration velocity of the particles differs through the length of the precipitator, this relationship more accurately predicts the collection behavior of a precipitator. Therefore, the values of $\tilde{\omega}_k$ that were calculated for the various voltage-airspeed combinations were used to estimate the collection efficiencies at different precipitator lengths and inter-electrode spacings.

6.5.6 The effective migration velocity (EMV)

The original and modified Deutsch-Anderson relationships were manipulated such that $\tilde{\omega}$ and $\tilde{\omega}_k$ were the independent factors. The values for $\tilde{\omega}$ and $\tilde{\omega}_k$ were calculated using equations 6-1 and 6-2, respectively. The values of L and S remained constant for the calculation of $\tilde{\omega}$ and $\tilde{\omega}_k$. The length of the precipitator, L, was 0.61 m and S, the inter-electrode spacing was 15 mm. The values of η_0, used in Equations 6-1 and 6-2 were the average overall collection efficiencies for each of the voltage-airspeed combinations. The values of $\tilde{\omega}$ and $\tilde{\omega}_k$ are given in Table 6-4. A sample calculation is available in Appendix F.

$$\tilde{\omega} = -\ln(1 - \eta_o/100)\cdot v\cdot S\cdot L^{-1} \qquad (6\text{-}1)$$

where: $\tilde{\omega}$ = effective migration velocity, $m\cdot s^{-1}$,
η_o = overall collection efficiency, %,
v = airspeed, $m\cdot s^{-1}$,
S = inter-electrode spacing, m, and,
L = length of electrostatic precipitator, m.

$$\tilde{\omega}_k = (-\ln(1 - \eta_o/100))^2\cdot v\cdot S\cdot L^{-1} \qquad (6\text{-}2)$$

where: $\tilde{\omega}_k$ = modified effective migration velocity, $m\cdot s^{-1}$,
η_o = overall collection efficiency, %,
v = airspeed, $m\cdot s^{-1}$,
S = inter-electrode spacing, m,
L = length of electrostatic precipitator, m.

Table 6-4 Original and modified effective migration velocities.

Voltage kVDC	Speed m/s	η_o %	$\tilde{\omega}$ mm/s	$\tilde{\omega}_k$ mm/s
-10.2	0.55	37.5	6.5	3.1
-10.3	0.76	22.2	6.2	2.0
-10.2	0.95	18.3	4.9	1.0
-11.1	0.55	45.6	8.2	4.8
-11.1	0.76	46.6	11.9	7.5
-10.9	0.95	47.5	15.3	9.9
-12.0	0.55	96.6	45.8	153
-12.1	0.76	90.5	46.0	112
-12.2	0.95	89.6	57.5	139

The values of $\tilde{\omega}$ varied from a minimum of 4.9 mm/s at applied voltage level 1 to a maximum of 57.5 mm/s at applied voltage level 3. The values of $\tilde{\omega}_k$ varied from a minimum of 1.0 mm/s at applied voltage level 1 to a maximum of 153 mm/s at applied voltage level 3. The $\tilde{\omega}$ and $\tilde{\omega}_k$ - applied voltage plots are shown in Figures 6-6 and 6-7, respectively.

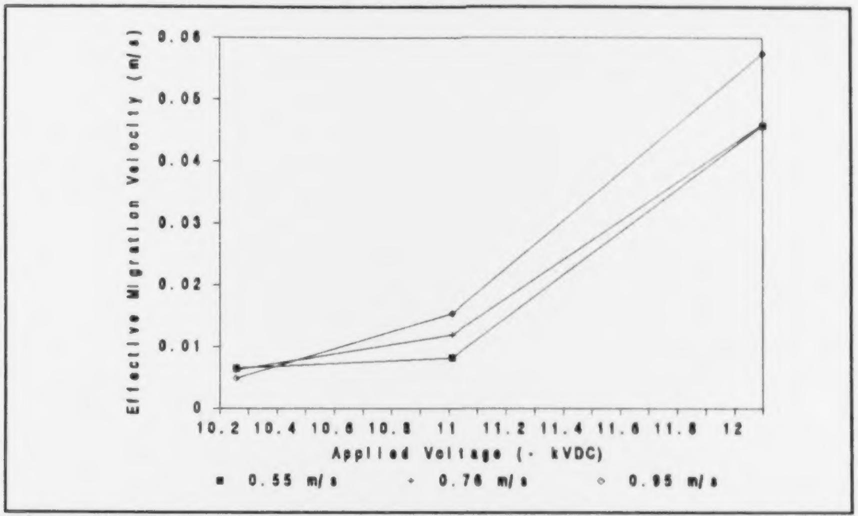

Figure 6.6 The effect of applied voltage and airspeed on effective migration velocity.

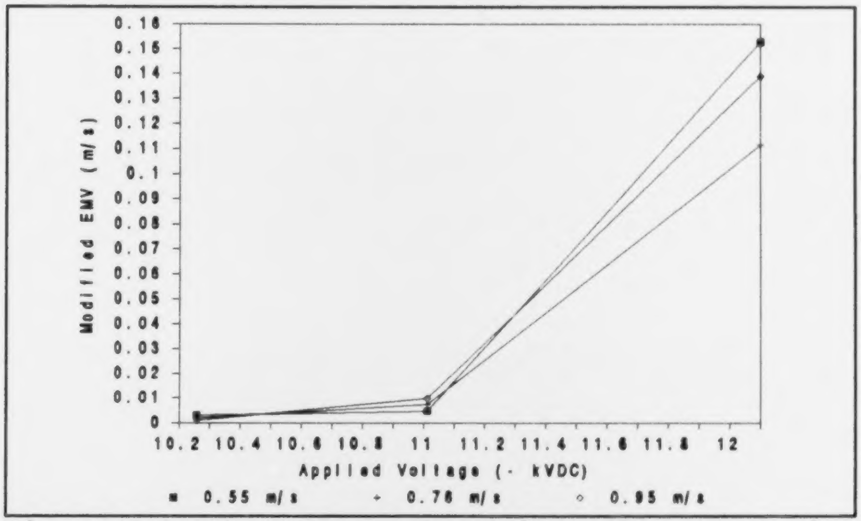

Figure 6.7 The effect of applied voltage and airspeed on modified effective migration velocity.

Airspeed produced little difference in $\tilde{\omega}$ and $\tilde{\omega}_k$ values at applied voltage levels 1 and 2. At applied voltage level 3, the values of $\tilde{\omega}$ and $\tilde{\omega}_k$ were much higher than at the lower applied voltages.

The large difference in effective migration velocity between applied voltage level 3 and levels 1 and 2 is due to the applied current at each of these levels. The applied current of 3 mA at applied voltage level 3, produced a stronger corona current thus propelling the particles toward the collection plate more quickly. The applied currents of 0.11 and 0.28 mA at applied voltages levels 1 and 2, respectively, are much lower than that at applied voltage level 3, thus resulting in much lower effective migration velocities.

The value of $\tilde{\omega}$ would only be used if the dust were homogeneous with all particles within a very small size range. Since swine housing dust is a heterogeneous mixture of constituents of different sizes, the value of $\tilde{\omega}_k$ is the more suitable value for effective migration velocity of the dust.

6.5.7 Effect of precipitator length

Using the modified Deutsch-Anderson relationship in Equation 2-12, collection efficiencies were estimated for precipitator lengths varying from 0.3 to 0.9 m. A sample calculation is given in Apendix G.

$$\eta_{ok} = 100 \cdot (1 - \exp(-(\tilde{\omega}_k \cdot L \cdot v^{-1} \cdot S^{-1})^{0.5})) \qquad (2\text{-}12)$$

where : η_{ok} = modified overall collection efficiency, %,
$\tilde{\omega}_k$ = modified effective migration velocity, $m \cdot s^{-1}$,
L = precipitator length, m,
v = airspeed, $m \cdot s^{-1}$, and
S = inter-electrode spacing, m.

At the original precipitator length of 0.61 m, the applied current densities for applied voltages levels 1, 2 and 3 were 0.02 mA/m^2, 0.05 mA/m^2 and 0.55 mA/m^2, respectively. Since the current density is directly related to the length of the collection plate, decreasing the precipitator length by half doubles the current density. Whereas, increasing the precipitator length halves the applied current density. These relationships are determined, assuming the applied current remains the same at the different precipitator lengths.

With a doubling of current density, collection efficiency is expected to increase, whereas a decrease in current density should lead to a decrease in collection efficiency. Neither one of these trends was apparent from the calculated results, implying that the Deutsch-Anderson relationship does not take current density into consideration.

Figure 6-8 shows the effect of precipitator length on collection efficiency at the different voltage levels at an airspeed of 0.76 m/s. The relationship between precipitator length and collection efficiency at airspeeds of 0.55 and 0.95 m/s are similar to that at an airspeed of 0.76 m/s.

At every voltage, the collection efficiency increases with increasing precipitator length. The estimated collection efficiencies for the precipitator length of 0.3 to 0.9 m, increased from 80.6% to 90.3%. Therefore tripling the precipitator length would lead to a 10% increase in collection efficiency. This may be useful only if a slight increase in efficiency is required.

The increase of collection efficiency with precipitator length could be due to the migration velocity of the dust particles.

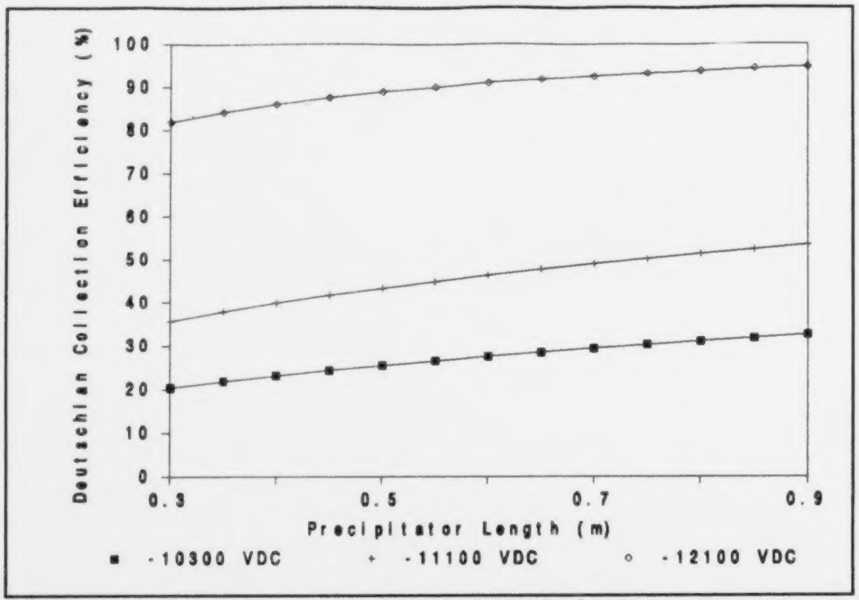

Figure 6.8 The effect of precipitator length on collection efficiency at an airspeed of 0.76 m/s.

Assuming the migration velocity and the air velocity through the precipitator remains the same, the residence time of a a particle in the precipitator increases with increasing precipitator length. As the collection plates become shorter, particles may escape. Even though, when increasing precipitator length, the current density would be decreased, the results show that only the residence time would change, and the current density remains the same.

6.5.8 Effect of inter-electrode spacing

As discussed in the Literature Review, the smaller the inter-electrode spacing, the stronger is the electric field near the discharge wire extending to zero at the collection plate. At a larger inter-electrode spacing, the charge within the inter-electrode space decreases to zero at the collection plate more uniformly. The magnitude of the electric field within the inter-electrode spacing remains constant, regardless of the distance between electrodes.

The collection efficiencies were calculated using Equation 2-12 based upon a precipitator length of 0.61 m and an inter-electrode spacing varying from 9 to 20 mm to demonstrate how sensitive this parameter is in the efficiency equation. The original inter-electrode spacing was 15 mm. The expected collection efficiencies decreased with increasing inter-electrode spacing. With a constant $\tilde{\omega}_k$ value, this was expected since as with air speed the inter-electrode spacing is within the denominator in Deutsch-Anderson relationship. The calculated collection efficiencies for varying inter-electrode spacing at an airspeed of 0.76 m/s are plotted in Figure 6.9. A sample calculation is given in Appendix H.

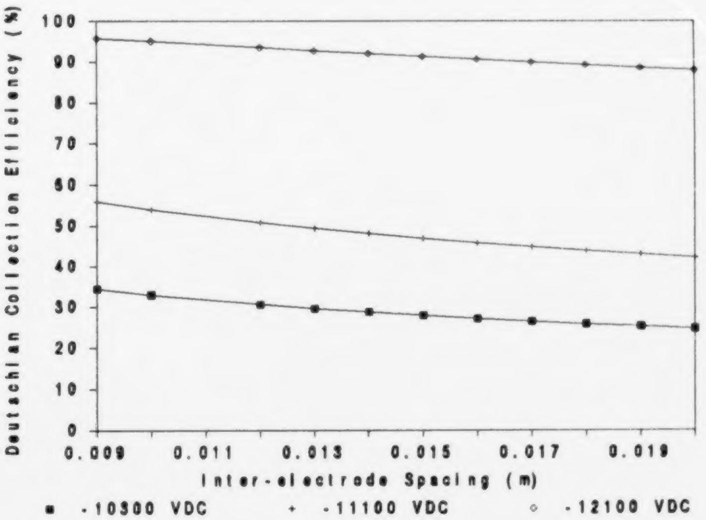

Figure 6.9 The effect of inter-electrode spacing on collection efficiency at an airspeed of 0.76 m/s.

The collection efficiency at applied voltage level 3 and an airspeed of 0.55 m/s at the original inter-electrode spacing of 15 mm, was approximately 96.4%. At the same voltage - airspeed combination, the collection efficiency varies from 98.7% to 94.5% for an inter-electrode spacing of 9 to 20 mm, respectively. Therefore, maintaining the same applied voltage, decreasing the inter-electrode spacing would increase the collection efficiency of an electrostatic precipitator, if ω_k remains constant for varying inter-electrode spacings. Since current density is based on collection area, it does not vary with inter-electrode spacing.

6.6 Ozone Production

The concentration of ozone was measured at the inlet of the electrostatic precipitator for each of the voltage - airspeed combinations. The concentrations measured by the gas detector varied from 0 to 0.27 ppm. Airspeed through the electrostatic precipitator would not have an effect on ozone production. Applied voltage and current on the other hand do affect ozone production. The ozone concentrations produced at voltage level 3, exceeded the recommended TLV of 0.1 ppm for an 8-h day, 40-h week.

Assuming that the ozone concentration measured within the chamber was similar to that removed by the exhaust fan, the total ozone production for each run was calculated. The average exhaust flows ranged from 976 to 4602 m^3/h, with an average of 2193 m^3/h. The total amount of ozone produced for the duration of each run varied from 0 to 333 mL/h. The mean ozone produced at applied voltage level 3 was 296 mL/h.

The ozone concentrations and the total amount removed by the exhaust fan are included in Table 6-5. The original ozone concentrations were adjusted by multiplying by the pressure factor, F. A strong odor of ozone was detected at applied voltage level 3. At the applied voltage level 1, no ozone was detectable, however ozone may have been produced in small quantities. A sample calculation is given in Appendix I.

Table 6-5 Ozone concentration.

Applied Voltage kVDC	Applied Current mA	Air-speed m/s	Exhaust Flow m^3/h	Ozone ppm	Ozone mL/h
-10.4	0.08	0.55	1400	*	*
-10.2	0.07	0.76	3890	*	*
-10.3	0.12	0.95	2420	*	*
-11.0	0.2	0.55	4600	0.04	184
-11.0	0.32	0.76	976	0.04	39
-10.8	0.22	0.95	1240	*	*
-12.2	2.95	0.55	1070	0.27	289
-11.9	3.4	0.76	3030	0.11	333
-11.9	2.8	0.95	1110	0.24	267

* - not detectable

7. DISCUSSION OF RESULTS

7.1 Particle Size Distribution

7.1.1 Experimental results

The majority of the particles in the aerial dust used in the experiment were between 1 and 2 μm. The count median diameter was approximately 1.7 μm and the average particle size was 1.9 μm. The frequencies of particles less than 1 μm, 2μm and 5 μm, were 21.2%, 61.5% and 98.2%, respectively.

7.1.2 Other studies

In a Danish study, the frequencies of airborne dust particles within the size ranges of 0.5 to 1.5 μm, 1.5 to 3 μm and 0.5 to 5 μm were 22%, 28% and 70%, respectively (Pedersen, 1990). In another study, 83 to 98% of all particles were within the size range of 1.8 to 6.9 μm (Heber et al., 1986). In a third study comparing the effects of different feeding methods and air temperature on dust levels, between 96.3% and 97.6% of the total aerial dust was less than 5 μm (Feddes et al., 1983).

7.1.3 Comparison of results

There were slightly more smaller particles in the dust used in this research as compared to previous studies. This may be due to the difference in sampling equipment, as well as varying environmental conditions. As previously discussed, a higher relative humidity leads to a higher settling rate of larger particles resulting in a higher percentage of smaller respirable particles. The type of animal housing and cleanliness also had an effect on aerial dust levels. The particle size distributions measured in this experiment was assumed to be representative of particle sizes found in swine confinement buildings. Since the particles are mainly within the respirable range of less than 3 μm, they can endanger the health of humans and animals, which supports the urgent need to remove them from the airspace.

7.2 Dust Constituents

7.2.1 Experimental results

The majority of constituents identified in the swine housing dust used in this experiment were starch and fecal particles. Fecal particles were identified as the majority of particles less than 5 μm. The starch particles were identified as the majority of particles greater than 5 μm. The other constituents identified in smaller amounts were: skin, plant hair, minerals (K and Cu) and bran.

7.2.2 Results from other studies

In other studies the particles identified in swine housing dust included: feed, fecal material, swine protein, mold, pollen, grain mites, insect parts, mineral ash, gram-negative bacteria, endotoxin, adsorbed ammonia, and infectious agents (Donham et al., 1986; Heber and Stroik, 1988). The majority of all particles were feed particles, however the majority of respirable particles were fecal particles.

7.2.3 Comparison of results

There was no identification of viable particles such as gram-negative bacteria, infectious agents or endotoxins in the microscopic identification of the constituents of dust used in this experiment. This may have been due to either insensitivity in the microscopic reading or the lack of these particles within the dust. Since the dust was collected and stored approximately 30 days before it had been used in the experiment, any viable particles should have lost their viability. The identification of particles less than 5 μm as being mainly fecal particles was common to the results of this experiment and other studies.

7.3 Aerial Particle Concentrations

7.3.1 Experimental results

The average airborne dust concentrations, Nt, varied from

22.2 to 51.8 particles/mL between runs with an average of 40.6 particles/mL. These concentrations were summations of all particles within the size range of less than 0.5 to 8 μm per unit volume. These dust concentrations were kept approximately uniform for each run, through control of the exhaust fan. The exhaust airflow varied from 976 to 4600 m^3/hr over all the experimental runs.

7.3.2 Other studies

Dust concentrations measured in other studies were 1.3, 1.4, 2.2 and 2.4 particles/mL (Feddes et al., 1983) and 9 and 12.2 particles/mL (Heber et al., 1988). The variation in results were dependent upon feeding methods, ventilation types and temperature as previously discussed. Variations between studies could be due to environmental factors as well as the type of sampling equipment used.

7.3.3 Comparison in results

The dust concentrations measured in actual swine confinement buildings were much less than those used in this experiment. The dust concentration of approximately 41 particles/mL is representative of periods of high activity in swine confinement buildings and represents the worst case scenario. The levels encountered in this research are higher than the recommended TLV of 37 particles/mL (Donham, 1987).

7.4 Overall Collection Efficiency

7.4.1 Experimental results

The electrostatic precipitator designed for this thesis was fabricated with stronger materials than the residential-type precipitators. The electrostatic precipitator was placed within the recirculation duct to remove both the electrical hazard as well as the collected dust from within the environmental chamber. Removing the collected dust from the recirculated air reduces the amount of dust to be re-entrained into the airstream.

The dust collection efficiencies calculated in this experiment were based on the ratios of dust concentration downstream from the precipitator to that upstream from the precipitator. Since the dust concentrations within the environmental chamber had to be kept approximately constant, a decay of dust levels with the use of the precipitator could not be measured.

The overall collection efficiencies are based upon the individual collection efficiencies for the particles within the size range of less than 0.5 to 8 μm. The overall collection efficiencies, η_o, varied between 18.6 and 96.4%, for the applied voltages of -10.2 kVDC and -12.0 kVDC, respectively. Using the least square means the standard error was calculated as 5.14.

7.4.2 Other studies

Experiments performed with fabric filters in swine housing yielded a 25% greater growth-rate between 3 and 7 weeks of age of early-weaned pigs in a rhinitis-infected herd (Carpenter, 1984).

One experiment performed with wet scrubbers, another mechanical dust removal system, resulted in the removal of 90% of particles > 5μm, 50% of particles > 1μm, and 21% of the total NH_3 measured (Licht and Miner, 1979). An alternate scrubber design resulted in the removal of 40% of particles, 25% of NH_3, 15% and 50% of micro-organisms (Pearson, 1986). Generally wet scrubbers are efficient in the removal of particles > 2μm and gases such as NH_3 and CO_2.

Several ionizer designs were tested and yielded various rates at which the dust concentration decayed down to approximately zero. Ionization was found to be more effective under zero ventilation than with ventilation, however ionization did increase the dust decay rate when used in conjunction with ventilation fans (Bundy, 1974). To decrease the amount of deposition of charged particles on the housing fixtures it was concluded that a collection device be placed near the charging mechanism, as in an electrostatic precipitator. Changes in humidity did not affect the ionization of dust particles, however air flows across collection plates did affect the retention of the dust (Bundy, 1974).

As compared to the decay rate of the dust particles without ionization, ionization produced a significant reduction in the number of particles greater than 0.5 μm within 30 minutes (Bundy and Veenhuizen, 1987). When compared to an ionization system in which charged ions were distributed using a recirculation duct, charging the ions directly within the room resulted in higher dust decay rates (Bundy and Veenhuizen, 1987). This may have been due to the decrease in electrical mobility of the ions as they travelled further from their source, resulting in a decrease of collisions between dust particles and ions.

The combination of particle charging and collection systems resulted in the design of various types of electrostatic precipitators. Commercial-type units have not been tested in swine housing but a unit was tested in an experiment using broiler chicken housing. A residential-type electrostatic precipitator with a rated dust collection efficiency of 99%, removed 52% of the total dust mass that had been previously filtered. The complete system of electrostatic precipitator and fabric filter yielded a combined removal efficiency of 98% (Williams, 1989). Half of the elements in the electrostatic precipitator were short-circuited by the second week of use, decreasing the collection ability of the unit.

In an experiment performed as preliminary research to this thesis research, swine housing dust was passed through a segment of a residential two-stage positive voltage electrostatic precipitator. The electrostatic precipitator that collected the swine housing dust with 67.3% efficiency had an efficiency rating of 99% (Fournier and Feddes, 1991).

Three electrostatic precipitators were designed based upon the ionization methods developed in previously discussed experiments. Systems 1, 2 and 3 yielded reductions of 48.6%, 52.8% and 53.7%, respectively (Veenhuizen and Bundy, 1990). The three systems differed in their wire-collection plate configuration with respect to the airflow within the chamber. The air movement patterns across the collector surface and ionizing electrode affects the collection efficiency of the ionizing system. A higher efficiency was yielded for design 3, which had the air flowing parallel to the length of the wires and collection plates, instead of across them (Veenhuizen and Bundy, 1990). The air flow across the collection plates and discharge electrodes would cause a greater amount of dust re-entrainment back into the airstream.

7.4.3 Comparison of results

The electrostatic precipitator precipitator used in this researcremoved up to 94% of dust particles. This efficiency is higher than those yielded by wet scrubbers and filters. Wet scrubbers are more efficient in removing irritating gases such as NH_3 and CO_2 (Pearson, 1988). However since gases are generally adsorbed onto a particle's surface, removing most of the particles would ultimately remove the gases. Ionization is an efficient method to charge dust particles, however it is most efficient when the ionization occurs within the chamber where the dust is present.

Combining any air cleaner with a recirculation fan and/or duct serves two purposes including: 1)Most of the air within the chamber is drawn through the air cleaner and 2)the recirculated air contains less dust. The electrostatic precipitator designed for this thesis research yielded very good collection efficiencies at suitable voltage and airspeed settings. Several improvements that could make this system a suitable alternative for livestock housing include: 1)Adding a self-cleaning mechanism; 2)building a suitable controller and power supply for the precipitator design; 3)using strong materials to prevent wear and bends and 4)selecting the proper lengths and spacings to optimize efficiency.

The remainder of the discussion will include the effects of changing design parameters such as airspeed, applied voltage, inter-electrode spacing and precipitator length on the prototype electrostatic precipitator used in this thesis research.

7.5 Effect of Voltage

The applied voltage level is one of the two independent parameters that was included in the experimental design. The values of voltage and corresponding current levels 1, 2 and 3 were approximately: -10.3 kVDC (0.11 mA), -11.0 kVDC (0.28 mA) and -12.1 kVDC (3.0 mA), respectively. The average collection efficiency for each of the applied voltage levels 1, 2 and 3 were: 28.0%, 46.3% and 92.9%, respectively. Applied voltage due to the corresponding applied current had a significant effect ($P<0.05$) on collection efficiency. Since the corresponding current for each of the voltage levels is dependent upon temperature current is the parameter that controls the strength of the corona discharge. Therefore, current should be the main parameter to be monitored in providing a consistent corona discharge.

The collection efficiency for voltage level 3, -12.1 kVDC (3.0 mA) at any of the three airspeed levels was higher than at lower applied voltages. The differences in applied current and collection efficiency between voltage level 3 and 2 are 2.72 mA and 51.2%, respectively. The differences in applied current and collection efficiency between voltage level 2 and 1 are 0.17 mA and 15%, respectively. The larger the difference in applied current, the larger the difference in effective migration velocity and thus collection efficiency. The applied current is a valuable tool in predicting collection efficiency.

7.6 Effect of Airspeed

The airspeed through the electrostatic precipitator was the other independent factor in the experimental design model. The three airspeed levels and corresponding airflows through the precipitator were: 0.55 m/s (244 m^3/h), 0.76 m/s (338 m^3/h) and 0.95 m/s (422 m^3/h), respectively. The average collection efficiency for each of the airspeed levels 1, 2 and 3 were: 59.6%, 55.2% and 52.41%, respectively. Airspeed did not have a significant effect ($P<0.05$) upon collection efficiency. Had the range of airspeed levels been broader it is expected that airspeed would have had a significant effect upon collection efficiency.

The speed at which a particle flows through an electrostatic precipitator affects the time that the particle is resident within the precipitator. The longer the particle remains within the precipitator, the higher the chance of particle charging and collection. If the particle passes through the precipitator without being fully charged it may not be collected. To migrate toward the collection plate, the particle must overcome the perpendicular drag force of the airflow through the precipitator.

The main observation of the dust collection that occurred in this experiment was that the dust collected upon an area of the collection plate directly parallel to the discharge wires, regardless of applied voltage. Had the drag force affected the migration velocity of the charged particle towards the plate, the dust particles would have collected slightly downstream from the discharge wires. Since this did not occur at any applied voltage or airspeed, the airspeeds appeared to be within an acceptable range at which the collection of the particles was not affected by airspeed.

The recommended airspeed range for electrostatic precipitators is between 0.3 and 6 m/s (Wark and Warner, 1981). Analysing the results for the overall collection efficiencies at the different airspeed levels, airspeed level 1 generally supplied the highest efficiencies. Therefore, based upon these results a low airspeed, such as 0.55 m/s would be recommended. However, since the airspeed is lower, the actual airflow and thus the number of particles passing through the unit per unit time would also be less as compared to those at higher airspeeds. The factored efficiencies based on an equivalence of particles per second were compared, and airspeed level 2 of 0.76 m/s yielded the highest factored efficiencies at all voltage levels.

In conclusion to these results, the airspeed of 0.76 m/s provides the optimal conditions (of the three airspeed levels tested) within the electrostatic precipitator for particle collection. At this airspeed the turbulence is such that the occurrence of collisions between particles and ions is higher than at a lower airspeed. However, there is a limit to the amount of turbulence that can be allowed before collection efficiency is decreased. At high speeds, excessive turbulence can cause collected particles to be bumped off the collection plate. As well, the higher airspeed of 0.95 m/s may have caused the particles to overcome the force due to their migration velocities and leave the precipitator before they were completely charged.

Based upon the overall and factored collection efficiencies, to optimize collection efficiency, the recommended applied voltage and air speed levels would be: -12.1 kVDC (3.0 mA) and 0.76 m/s, respectively. The following sections discuss how collection efficiencies could be improved as well as how high efficiencies may have to be sacrificed to reduce the hazardous effects of ozone.

7.7 Effective Migration Velocity (EMV)

The effective migration velocity, ω, represents the migration velocity of all the dust particles towards the collection plate. Using the original and modified Deutsch-Anderson equations the values of ω and ω_k, are directly proportional to the overall collection efficiency, η_o, the airspeed, v and the inter-electrode spacing, S (Lloyd, 1988). ω and ω_k are inversely proportional to the length of the precipitator, L (Lloyd, 1988).

Applied voltage had a greater effect upon the values of ω and ω_k, than did airspeed through the precipitator. The average values of ω for voltage levels 1, 2 and 3 were: 5.9 mm/s, 11.8 mm/s and 49.8 mm/s, respectively. The average values of ω for airspeed levels 1, 2 and 3 were: 20.2 mm/s, 21.4 mm/s and 25.9 mm/s, respectively. The average values of ω_k for voltage levels 1, 2 and 3 were: 2.0 mm/s, 7.4 mm/s and 134 mm/s, respectively. The average values of ω_k for airspeed levels 1, 2 and 3 were: 53.5 mm/s, 40.4 mm/s and 50 mm/s, respectively.

The average migration velocity, based on individual particles, for particles < 5 μm is less than 0.3 m/s (Lloyd, 1988). For the smaller particles in fly ash, which usually range in size from 1 to 10 μm, the average migration velocity typically lies between 0.01 to 0.2 m/s (Lloyd, 1988). Since the swine housing dust used in this experiment is generally < 5 μm, the effective migration velocity values should be similar to the average migration velocity of dust within the same size range. The average values of $\tilde{\omega}$ and $\tilde{\omega}_k$ were slightly higher than average migration values. This may have been due to different operating conditions under which the migration velocities were calculated or since the effective migration velocity must compensate for a broader size range of particles.

As previously discussed, the drift speed of particles is lowest for particles with a diameter of 0.2 μm (Lloyd, 1988). The particles with a diameter close to 0.2 μm would be collected later in the precipitator, whereas the particles less than and greater than 0.2 μm are collected sooner. The modified version of the Deutsch-Anderson relationship takes into account that particles of different sizes are collected at different locations throughout the precipitator. This was demonstrated by the microscopic analysis performed on the dust collected from the front and back sections of the collection plate. The distribution of particles collected on the plate were not uniform, with most of the very small fecal particles being collected near the inlet as compared to the outlet.

Therefore the effective migration velocity of importance for the swine housing dust used, is the modified EMV, $\tilde{\omega}_k$. Generally the values of $\tilde{\omega}_k$, increased with increasing applied voltage. At applied voltage levels 1 and 3, the highest $\tilde{\omega}_k$ was at the air speed of 0.55 m/s. At applied voltage level 2, the highest $\tilde{\omega}_k$ was at the air speed of 0.95 m/s. These trends resemble the trends in collection efficiency for the air speed and voltage levels.

7.8 Effect of Electrostatic Precipitator Length

The modified Deutsch-Anderson relationship was used to determine the expected collection efficiency at varying precipitator lengths using the average modified effective migration velocities. For every applied voltage and airspeed, the expected collection efficiency was increased with increasing precipitator length. By increasing the precipitator length by 50%, the collection efficiency at an applied voltage of -10.3 kVDC, could be increased by approximately 4.8%. At an applied voltage of -11.0 kVDC, increasing the precipitator length by half could increase the collection efficiency by approximately 6.7%. At an applied voltage of -12.1 kVDC, increasing the precipitator length by half could increase the collection efficiency by approximately 3.0%.

The increase in collection efficiency with increasing length is due to a longer residence time within the precipitator. The increased length allows the particles not fully charged to attain more charge and be collected upon the collection plate. As well, the particles with lower migration velocities may need a longer residence time during which to reach the collection electrode. This is especially true when the applied voltages are low and do not supply strong corona, resulting in lower values for EMV and a lower electric field within the inter-electrode spacing.

Increasing the precipitator length may not contribute greatly to an increase in collection efficiency, however it can be used as a tool in optimizing precipitator length. Current density should also be considered since precipitator length does affect this parameter.

7.9 Effect of Inter-Electrode Spacing

The modified Deutsch-Anderson relationship was used to determine the expected collection efficiencies at varying inter-electrode spacing using average values of EMV previous calculated. The expected collection efficiencies generally decreased with increasing inter-electrode spacing. These results may not have been realistic since an increase in inter-electrode spacing results in an increase in EMV (Lloyd, 1988). Therefore the assumption that the EMV remains the same for varying inter-electrode spacings is incorrect.

The results showed that for an applied voltage of -10.3 kVDC increasing the inter-electrode spacing by 31% the collection efficiency would be decreased by 3.1%. At an applied voltage of -11.0 kVDC, a 31% increase in inter-electrode spacing resulted in a 4.4% decrease in collection efficiency. At an applied voltage of -12.1 kVDC, a 31% increase in inter-electrode spacing resulted in a 2.8% decrease in collection efficiency. These results were calculated using a constant effective migration velocity.

Had the EMV values increased with inter-electrode spacing, as expected and depicted in Figure 2.12, the ratio of $\tilde{\omega}_k/S$ as used in the modified Deutsch-Anderson equation would remain approximately constant. The collection efficiencies may actually not be affected by inter-electrode spacing, within a certain range. The change in EMV with inter-electrode spacing for this specific electrostatic precipitator, could not be estimated without actual testing.

Assuming that the inter-electrode spacing has little effect upon collection efficiency, the spacing could be increased slightly to reduce the effect of bent or misaligned electrodes. As was observed, a couple of bent electrodes within the prototype unit resulted in corrosion of two collection plates. Had the inter-electrode spacing been increased, the corrosion of the collection plates may have been reduced, without reducing the collection efficiency. Bent or misaligned electrodes are common especially in older units (Lloyd, 1988), therefore it is best to make provisions for such occurrences.

7.10 Ozone Production

The concentrations of ozone, (O_3), varied from 0 ppm at an applied voltage of -10.3 kVDC to 0.27 ppm at an applied voltage of -12.2 kVDC. The recommended TLV for (O_3), for an 8-h day 40-h week, is 0.1 ppm (ACGIH, 1985). At an applied voltage of -12.1 kVDC, the mean O_3 produced was 0.21 ppm. Assuming these concentrations would be constant during an entire day of precipitator operation the TLV was exceeded, at voltage level 3. The maximum concentration of 0.3 ppm is not to be exceeded for more than 15 min. (ACGIH, 1985). This value was not exceeded for any run.

The concentration of (O_3) at the applied voltage of -12.1 kVDC, was lowest when the exhaust fan was operating at maximum capacity. To reduce the concentrations present in the chamber, the exhaust fan could be operated accordingly. This may not be a practical tool if the ventilation rate required to control the ozone level, exceeds the winter and/or summer ventilation rates. Assuming that the concentrations were at equilibrium, the total amount of (O_3) produced during an entire run of 1-h was estimated to be 19 mL/m of discharge wire.

The mean (O_3) produced, at an applied voltage of -12.1 kVDC was 296 mL/h (97.1 mL/h/mA). At this production rate the ozone must be diluted to 0.21 ppm by room ventilation or 24 air changes/h.

The concentrations produced at the lowest applied voltage level could not be detected. The mean concentration produced at the applied voltage level of -11.0 kVDC was 0.03 ppm. The concentration at which the odor of (O_3) can be detected by a human is 0.02 ppm (Rice and Browning, 1973). Therefore, at the applied voltage level of -11.0 kVDC, (O_3) would be detected by the human nose. Nasal and throat irritations would occur at 0.3 ppm (Rice and Browning, 1973).

8. Conclusions

The following conclusions are drawn from this study:

1. The applied voltage and current levels of -10.3 kVDC (0.11 mA), -11.0 kVDC (0.28 mA) and -12.1 kVDC (3.0 mA) had a significant effect ($P < 0.05$) upon collection efficiency of the prototype electrostatic precipitator.

2. The three levels of airspeeds through the precipitator, of 0.55 m/s (244 m^3/h), 0.76 m/s (338 m^3/h) and 0.95 m/s (422 m^3/h) did not have a significant effect ($P < 0.05$) upon collection efficiency of the prototype electrostatic precipitator.

3. The overall efficiency, η_o, increased from 18.6% at an applied voltage of -10.3 kVDC to 96.4% at an applied voltage of -12.1 kVDC.

4. To optimize particle removal, the airspeed of 0.76 m/s should be used at applied voltages between -10.3 to -12.1 kVDC.

5. The modified effective migration velocity, $\tilde{\omega}_k$, of the particles increased by 66% when increasing the applied voltage from -10.3 to -12.1 kVDC.

6. When applying a voltage and current of -12.1 kVDC (3 mA), the ventilation rates should be sufficient to reduce ozone production and adverse health effects on humans and animals.

7. Combining a recirculation duct, self-cleaning mechanism and power supply controller with an electrostatic precipitator is an effective method of dust removal for swine confinement housing.

9. Recommendations

Research into the use of an electrostatic precipitator in conjunction with a recirculation duct as a dust removal method for swine confinement housing should be continued. The operating voltage and current should be near -12.1 kVDC and 3 mA, respectively, for the prototype design, however with high levels of (O_3) being produced this should be re-evaluated. Several parameters could be adjusted to limit the (O_3) production to within allowable concentrations, such as : 1)Change the polarity of the power supply to positive voltage; 2)decrease the applied voltage, increase the precipitator length and increase the inter-electrode spacing; 3) use a 2-stage wire-plate precipitator and/or 4)use a charcoal filter to remove the (O_3).

The optimal levels of positive applied voltage would have to be tested since positive voltage does not behave the same as negative voltage. The power supply and controller could be adjusted around the design of the precipitator, as in this research where voltage levels were selected based on the behavior of the corona discharge. A controller should be used in conjunction with the power supply to maintain the desired current throughout operation of the unit. The controller could also be used to signal a cleaning mechanism once the current reaches a maximum level. The recommended cleaning mechanism should be able to operate without short-circuiting the power supply and should limit the amount of dust re-entrainment.

Based upon the prototype design and the type of dust collected, a rapper may not be a suitable cleaning mechanism. When dry-cleaned with a sponge the dust retained its charge and was quite difficult to completely remove. A rapping or vibration device may be sufficient to remove the dust from the discharge wires. A wiper style device which traverses down the collection plate may be a suitable cleaner, however the inter-electrode spacing should be large enough to accomodate the wiper, to avoid short-circuiting of the system if the discharge wire and wiper were to come into contact.

It is recommended that the electrostatic precipitator be removed from the immediate vicinity of a human's or animal's environment, due to electrical hazards and the excessive production of (O_3). The recirculation fan could be used to transport the dust-laden air into an adjoint chamber which houses the precipitator. The cleaned air could then be filtered free of (O_3) and be recirculated back into the animal chamber. Proper grounding and insulation should be employed to reduce the chance of people and animals coming into contact with free-flowing current.

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11. APPENDICES

Appendix A: Deutsch-Anderson Derivation

The derivation of the Deutsch-Anderson relationship was taken from Lloyd (1988). Consider an elemental length of the precipitator δx, situated x from the precipitator inlet. A volume of the precipitator bounded by the two rectangles ABCD and A'B'C'D', spaced δx apart, parallel to each other and normal to the gas flow is depicted in Figure A.1. ABCD is x from the precipitator inlet. The gas flows at a velocity (v) which is uniform over the cross-section of the precipitator. It is assumed that no gas or dust crosses the planes AA'D'D, AA'B'B and DD'C'C. Only dust particles cross the boundary BB'C'C that touches the collection electrode.

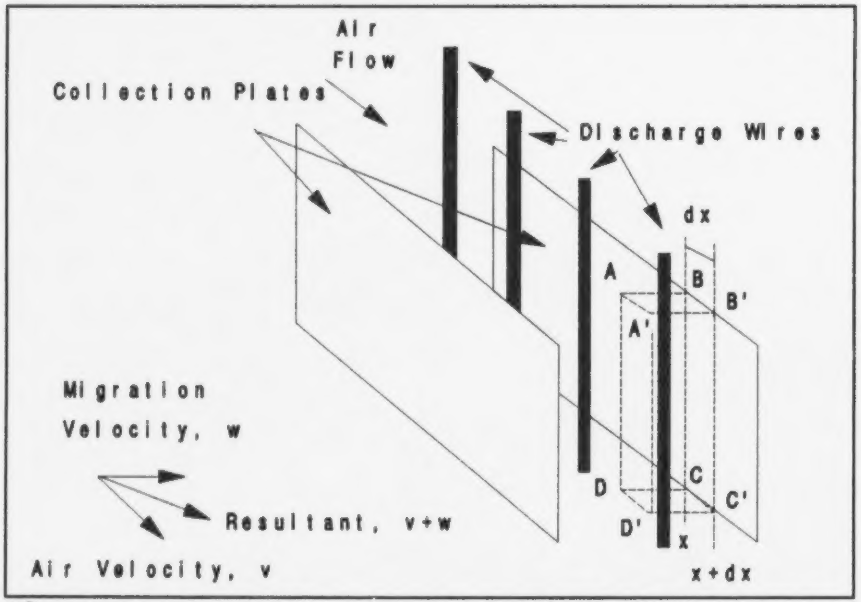
Air Flow
Collection Plates
Discharge Wires
dx
A
B
B'
A'
Migration Velocity, w
C
D
C'
D'
x
Resultant, v+w
Air Velocity, v
x+dx

Figure A.1 Schematic for the Deutsch-Anderson relationship. Adapted from Lloyd, (1988).

The concentration of the dust entering the face ABCD is $C_{(x)}$ and the dust leaving the face A'B'C'D' has a concentration of $C_{(x+\delta x)}$. The average dust concentration over the face of the volume next to the collection electrode (BB'C'C) is taken as

$[C_{(x)}+C_{(x+\delta x)}]/2$. The expressions for the dust entering and leaving the elementary volume per unit time are as follows:

$$\begin{aligned}
\text{Dust entering} &= C_{(x)}\cdot(\text{volume of gas entering per unit time})\\
&= C_{(x)}\cdot v\cdot(\text{area ABCD}).\\
\text{Dust leaving} &= C_{(x+\delta x)}\cdot v\cdot(\text{area A'B'C'D'})\\
&\quad +\tilde{\omega}\cdot(\text{area BB'C'C})\cdot[C_{(x)}+C_{(x+\delta x)}]/2.
\end{aligned}$$

The dust leaving was equated with that entering, resulting in:

$$\begin{aligned}
C_{(x)}\cdot v\cdot(\text{area ABCD}) &= C_{(x+\delta x)}\cdot v\cdot(\text{area A'B'C'D'})\\
&\quad +\tilde{\omega}\cdot(\text{area BB'C'C})\cdot[C_{(x)}+C_{(x+\delta x)}]/2.
\end{aligned}$$

A variable H was used to represent the height of the element, so that H=AD=A'D'=BC=B'C'. The variable S, represents the distance from the discharge electrode to the collecting electrode, so that S=AB=A'B'=DC=D'C'. The equation becomes:

$$C_{(x)}\cdot v\cdot H\cdot S = C_{(x+\delta x)}\cdot v\cdot H\cdot \delta x\cdot[C_{(x)}+C_{(x+\delta x)}]/2.$$

Rearranging the equation results in:

$$[C_{(x)}-C_{(x+\delta x)}]\cdot S = [C_{(x)}+C_{(x+\delta x)}]\cdot 0.5\cdot\tilde{\omega}\cdot v^{-1}\cdot\delta x.$$

In the limit, as δx tends to zero, the dust concentration at the downstream face of the elemental volume of the precipitator tends towards that at the inlet. As well, the average concentration over the face BB'C'C, approaches that over the upstream face, or $C_{(x)}\cdot[C_{(x)}-C_{(x+\delta x)}]$ can be expressed as $-\delta C$, therefore:

$$-\delta C = C_{(x)}\cdot\tilde{\omega}\cdot v^{-1}\cdot S^{-1}\cdot\delta x \text{ or } -C_{(x)}{}^{-1}\cdot\delta C = -\tilde{\omega}\cdot v^{-1}\cdot S^{-1}\cdot\delta x.$$

In the limit, as δx tends to zero, the result is:

$$C_{(x)}^{-1} \cdot dC = -\tilde{\omega} \cdot v^{-1} \cdot S^{-1} \cdot dx.$$

Integration of both sides resulted in:

$$\ln C_{(x)} = -\tilde{\omega} \cdot v^{-1} \cdot S^{-1} \cdot x.$$

Taking limits at x=0 and x=L (L=length of the precipitator),

$$[\ln C_{(L)} - \ln C_{(0)}] = -\tilde{\omega} \cdot v^{-1} \cdot S^{-1} \cdot [L-0)$$

or

$$\ln [C_{(L)} \cdot C_{(0)}^{-1}] = -\tilde{\omega} \cdot v^{-1} \cdot S^{-1}.$$

$C_{(L)} \cdot C_{(0)}^{-1}$, is the ratio of the dust burden at the precipitator outlet to the dust burden at the precipitator inlet, which is the slip or penetration. Representing slip by the symbol \$, the relationship becomes:

$$\ln \$ = -\tilde{\omega} \cdot L \cdot v^{-1} \cdot S^{-1},$$

or

$$\$ = \exp(-\tilde{\omega} \cdot L \cdot v^{-1} \cdot S^{-1}).$$

The above is one version of the original Deutsch-Anderson relationship. Written in terms of the collection efficiency of the precipitator, the relationship is:

$\eta = 100 \cdot [1 - \exp(-\tilde{\omega} \cdot L \cdot v^{-1} \cdot S^{-1})]$, where η is the per cent collection efficiency.

APPENDIX B: Airspeeds Through the Electrostatic Precipitator

The airspeeds through the electrostatic precipitator may vary due to turbulence. The average airspeed through the precipitator is estimated using the following method. Figure B.1 represents the cross-section of the recirculation duct downstream of the electrostatic precipitator. The width of the duct through which the air flows is represented by a=37.5 cm. The height of the duct is represented by b=36.8cm.

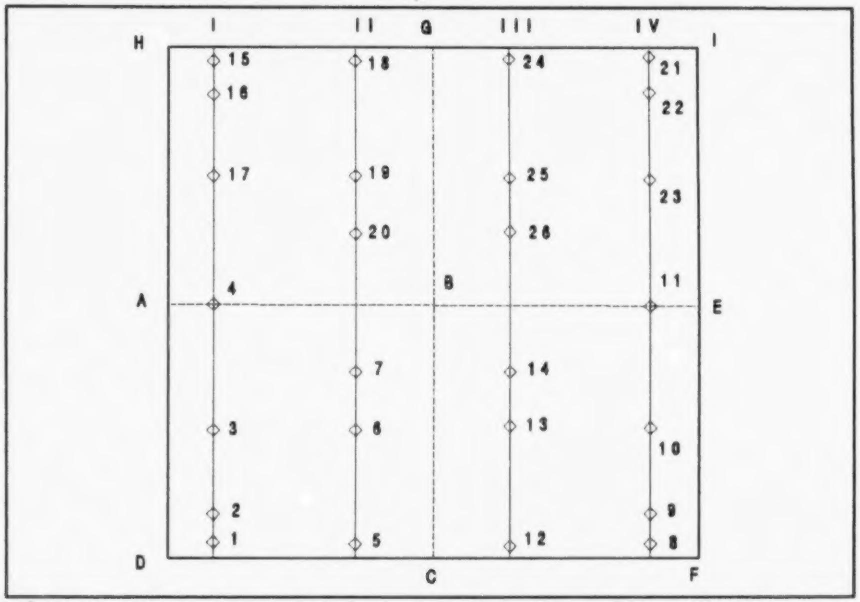

Figure B.1 Schematic of the 26-point system for airspeed measurement. Adapted from Ower and Pankhurst, (1977).

Using the method for measuring airspeed in a rectangular duct (Ower and Pankhurst, 1977), 26 airspeed measurement lcations were selected. Measurement locations 1,2,3,4,17,16 and 15 on Column I were located 3.4 cm from the wall. Measurement locations 5,6,7,20,19 and 18 on Column II were located 13.8 cm from the wall. Measurement locations 12,13,14,26,25 and 24 on Column III were located 23.7 cm from the wall. Measurement locations 8,9,10,11,23,22 and 21 on

Column IV were located 34.0 cm from the wall and 3.4 cm from the enclosure.

The vertical locations of airspeed measurements were in 9 rows along the height of the duct. The 1st row, including locations 1,5,12 and 8 was 1.2 cm from the base of the duct. The 2nd row, represented by locations 2 and 9 is 3.4 cm above the base of the duct. The 3rd row, represented by locations 3,6,13 and 10 is 9.2 cm above the base of the duct. The 4th row of measurements, represented by by locations 7 and 14 is 13.5 cm above the base of the duct. The 5th row of measurements, represented by locations 4 and 11 is 18.4 cm above the base of the duct. The 6th row of measurements, represented by locations 20 and 26 is 23.3 cm above the base of the duct. The 7th row of measurements is represented by locations 17,19, 25 and 23 is 27.6 cm above the base of the duct. The 8th row of measurements, represented by locations 16 and 22 is 33.4 cm above the base of the duct. The 9th row of measurements, represented by locations 15,18,24 and 21 is 35.6 cm from the base of the duct.

The entire duct is separated into 4 quadrants, ABCD, BEFC, HGBA and GIEB. The airspeed through each quadrant is as follows:

$$
\begin{aligned}
v_{ABCD} &= 1/24\cdot[2\cdot(v_1+v_2) + 5\cdot v_3 + 3\cdot(v_4+v_5+v_6) + 6\cdot v_7],\\
v_{BEFC} &= 1/24\cdot[2\cdot(v_8+v_9) + 5\cdot v_{10} + 3\cdot(v_{11}+v_{12}+v_{13}) + 6\cdot v_{14}],\\
v_{HGBA} &= 1/24\cdot[2\cdot(V_{15}+v_{16}) + 5\cdot v_{17} + 3\cdot(v_4+v_{18}+v_{19}) + 6\cdot v_{20}],\\
v_{GIEB} &= 1/24\cdot[2\cdot(v_{21}+v_{22}) + 5\cdot v_{23} + 3\cdot(v_{11}+v_{24}+v_{25}) + 6\cdot v_{26}].
\end{aligned}
$$

The average airspeed through the duct, v_m is calculated using the airspeeds measured through each quadrant.

$$v_m = 1/4\cdot[v_{ABCD} + v_{BEFC} + v_{HGBA} + v_{GIEB}]$$

The airspeeds were measured at three settings of the recirculation fan controller. Speed 1, refers to the minimal speed capable by the recirculation fan. Speed 3, refers to the maximum speed capable by the recirculation fan. Speed 2 was approximately mid-way between speeds 1 and 3. The airspeeds averaged over three samples for each of the 26 positions in the duct at each of the three airspeed levels 1,2 and 3 are given in Table B-1. The average airspeeds, v_m, for the entire duct at airspeed levels 1,2 and 3 were 0.51, 0.70 and 0.88 m/s, respectively. Due to the differences in atmospheric pressure between the elevation of Edmonton and sea-level during the month of May, 1991, a pressure factor F, of 1.08 was multiplied to the three airspeed values. Therefore, the average airspeeds through the duct adjusted for air pressure, were 0.55, 0.76 and 0.95 m/s.

Table B-1. Airspeed measurements used to calculate the average airspeed.

Location	Speed level 1	Speed level 2	Speed level 3
1	0.28 m/s	0.38 m/s	0.49 m/s
5	0.11 m/s	0.12 m/s	0.15 m/s
12	0.22 m/s	0.13 m/s	0.19 m/s
8	0.12 m/s	0.24 m/s	0.31 m/s
2	0.37 m/s	0.46 m/s	0.56 m/s
9	0.31 m/s	0.36 m/s	0.52 m/s
3	0.61 m/s	0.82 m/s	1.04 m/s
6	0.54 m/s	0.71 m/s	0.89 m/s
13	0.51 m/s	0.72 m/s	0.85 m/s
10	0.44 m/s	0.52 m/s	0.72 m/s
7	0.60 m/s	0.81 m/s	1.01 m/s
14	0.56 m/s	0.77 m/s	0.98 m/s
4	0.62 m/s	0.86 m/s	1.09 m/s
11	0.48 m/s	0.59 m/s	0.81 m/s

20	0.62 m/s	0.87 m/s	1.07 m/s
26	0.62 m/s	0.85 m/s	1.06 m/s
17	0.64 m/s	0.87 m/s	1.12 m/s
19	0.62 m/s	0.87 m/s	1.12 m/s
25	0.61 m/s	0.85 m/s	1.07 m/s
23	0.50 m/s	0.69 m/s	0.87 m/s
16	0.61 m/s	0.88 m/s	1.04 m/s
22	0.50 m/s	0.68 m/s	0.83 m/s
15	0.61 m/s	0.83 m/s	1.13 m/s
18	0.58 m/s	0.89 m/s	1.07 m/s
24	0.58 m/s	0.76 m/s	1.06 m/s
21	0.49 m/s	0.67 m/s	0.80 m/s
v_{ABCD}	0.49 m/s	0.65 m/s	0.82 m/s
v_{BEFC}	0.39 m/s	0.53 m/s	0.70 m/s
v_{GIEB}	0.55 m/s	0.74 m/s	0.95 m/s
v_{HGBA}	0.62 m/s	0.87 m/s	1.09 m/s
v_m	0.51 m/s	0.70 m/s	0.88 m/s
$v=v_m \cdot F$	0.55 m/s	0.76 m/s	0.95 m/s

Appendix C: Basica Program for Data Acquisition

```
10 '
20 '
30 '
4                                                        0    '
*************************************************************
50 '    Data collection program for APS and control of ball
60 '              valves through the Dascon-1
70 '     valves 1 to 5 used for sampling, valve 6 draws
filtered
80 '                 air between samples.
90 '      Revised  April  15,  1990  by  Susan  Fournier  for
electrostatic
100 '             precipitation experiment.
1                          1                             0    '
*************************************************************
120 '
130 '                INITIALIZATION OF VARIABLES
140 '
150 CLEAR, 32768!, 512
160 TIMER ON
170 ON TIMER (40) GOSUB 1700
180 '
190 '
200 OPEN "COM1:300,N,8,1,CS,DS,CD,RS" AS #3
210 OPEN "B:DATALOG.DAT" FOR OUPUT AS #4
220 '
230 '
240 GOSUB 2110
250 KEY OFF:CLS:SCREEN 2:LOCATE 10,9:PRINT "INITIALIZATING
VARIABLES":DEF SEG=64:POKE 23,96
260 '
270 DIM A(1023),CH(52),F(52),N(17),AR(17),DIO%(8)
280 X=0:Y=0:PASS%=0
290 ST=0:Z5=0:TN=0
300 DS(0)=20:SN=1:IN=48
310 '
320 OPEN "APS.CAL" FOR INPUT AS #1:INPUT #1,HS,FS
330 '
340  FOR  X=0  TO  52  :INPUT  #1,CH(X),F(X):NEXT  X:CLOSE
#1:SH=0:SF=0:FOR X=0 TO 52:SH=SH+CH(X):SF=SF+F(X):NEXT X:if
ABS(SH-HS)>0.1 THEN 370
350 FOR X=1 TO 17 :READ N(X) :NEXT X
360 IF ABS(SF-FS)<0.001 THEN 390
370 LOCATE 10,10:PRINT"CALIBRATION DATA NOT VALIDATED":END
380 '
390 CLS:LOCATE 10,20:INPUT "PARTICLE SAMPLING TIME SEC. ";DS
400 IF DS>0.001 THENDS(0)=DS
410  CLS:LOCATE  10,15:INPUT  "NUMBER  OF  SAMPLES  NEEDED  PER
SAMPLING TUBE ";SN
420 IF SN<0.001 GOTO 410
```

```
430 CLS:LOCATE 10,22:PRINT "TIME INTERVAL BETWEEN
SAMPLES":LOCATE 12,20:INPUT "MINUTES OR HOURS (TYPE M OR
H)';I$
440 IF I$="M" THEN T=60:T$="MIN":ELSE IF I$="H" THEN
T=3600:T$"HOUR"
450 CLS:LOCATE 10,20:PRINT "ENTER TIME ";T$:LOCATE 10,34:INPUT
S$:IF Z5=1 GFOTO 1160
460 IF S$="" GOTO 450
470 CLS:LOCATE 10,20 :INPUT "NAME OF FILE TO STORE DATA ";DN$
480 IF DN$="" GOTO 470
490 '
500 GOTO 1390
510 CLS:LOCATE 10,20:PRINT "TSI AERODYNAMIC PARTICLE
SIZER":FOR X=1 TO 1000:NEXT X
520 '
530 DEF USR0=IN:DEF USR1=IN+5:DEF USR2=IN+10:DEF
USR3=IN+15:DEF USR4=IN+20:DEF USR5=IN+25:DEF USR6=IN+30:
AD=IN+50: ER=AD+6: OV=ER+1:OT=OV+1
540 DEF SEG=&H1F74:BLOAD "O-APS1-2":X=USR0(0)
550 '
560 '
570 'CLEAR ACCUMULATOR
580 CLS:LOCATE 10,10:PRINT "ACCUMULATOR BEING CLEARED":POKE
ER,0:POKE OV,0:X=USR2(0): IF PEEK(ER)<>0 THEN LOCATE
20,4:PRINT "ACCUMULATOR FAILED VALIDATION
TEST":BEEP:BEEP:BEEP:FOR X=1 TO 1000:NEXT X
590 '
600 ST=0
610 '
620 'RUN
630 Z5=0:TI=DS(0)::POKE OT+1, INT (TI/256):POKE OT,TI-
INT(TI/256) * 256: X=USR5(0):CLS:LOCATE 10,30:PRINT "SAMPLING
PARTICLES"
640 '
650 NT=PEEK(OT+1)*256+PEEK(OT):IF INKEY$=CHR$(27) THEN
XUSR1(0): ST=ST+TI-NT:CLS:LOCATE 10,10:PRINT "READ ACCUMULATOR
?"ELSE GOTO 680
660 '
670 I$=INKEY$:IF I$="" GOTO 670 ELSE GOTO 760
680 IF PEEK(OV)<>0 THEN X=USR1(0):ST=ST+TI-NT:GOTO 820
690 IF NT=0 THEN ST=ST+TI:GOTO 810
700 GOSUB 2110
710 LOCATE 10,25:PRINT "TIME REMAINING IN SAMPLE : ";NT
720 GUSUB 2110
730 LOCATE 12,20:PRINT "SAMPLE BEING TAKEN FROM TUBE NUMBER :
";TN
740 LOCATE 19,18:PRINT "NUMBER OF PARTICLES PER ML. FROM LASTY
SAMPLE"
750 LOCATE 21,16:PRINT USING "####### < 5 MICRONS AND #######
> 5 MICRONS";AP1,AP2 : GOTO 650
760 IF I$="N" THEN GOTO 510
770 IF I$="T" THEN GOTO 510
```

```
780 IF I$<>"Y" THEN I$=INKEY$: GOTO 760
790 '
800 '
810 CLS:LOCATE  10,25:PRINT "COMBINING AND STORING DATA"
820 X=USR4(VARPTR(A(0)))
830 '
840 FOR X=1 TO 17 AR:(X)=0:NEXT X
850 FOR X=1 TO 16
860     FOR NU=N(X) TO N(X+1)
870         AR(X)=AR(X)+A(NU)
880     NEXT NU
890 NEXT X
900 '
910 FOR X=N(17) TO 1023
920     AR(17)=AR(17)+A(X)
930 NEXT X
940 FOR X=1 TO 6 : AP1=AP1+AR(X) : NEXT X
950 FOR X=7 TO 17 : AP2=AP2+AR(X) : NEXT X
960 '
970 ' The following calculation determines the number of
particles per mL.
980 ' AP1 is the variable for particles less than 5 microns
990 ' AP2 is the variable for particles greater than 5 microns
1000 'These calculations are for a dilution ratio of 1 to 1.
1010 'If the sample is diluted the values for AP1 and AP2 will
have to
1020 'be multiplied by the dilution ratio. The rest of the
data will
1030 'also have to be multiplied by dilution ratio.
1040 '
1050 AP1=AP1/(DS(0)*16.667) : AP2=AP2/(DS(0)*16.667)
1060 '
1070 N=N+1:OPEN "B:"+DN$ FOR APPEND AS #1:FOR X=1 TO 17: WRITE
#1, AR(X):NEXT X:CLOSE #1
1080 IF SN=(N/5) AND TN=5 GOTO 2100
1100 GOTO 1380
1110 '
1120 '            Time interval between samples
1130 '
1140 IF I$="M" AND VAL(S$)>0 AND VAL(S$) <= 1440 THEN 1170
ELSE 1150
1150 IF I$="H" AND VAL(S$) > 0 AND VAL(S$) <=24 THEN 1170 ELSE
1160
1160 BEEP:FOR X=1 TO 100:NEXT X:BEEP:FOR X=1 TO 100:NEXT
X:BEEP:LOCATE 10,30:PRINT "IMPROPER TIME ":Z5=1:GOTO 450
1170 TM=T*VAL(S$)
1180 '
1190 ' SET INITIAL TIME TO ZERO
1200 '
1210 TIME$="00:00:00"
1220 '
1230 '
```

```
1240 '
1250 '
1260 T$=TIME$
1270 TH$=MID$(T$,1,2):TH=VAL(TH$):THM=TH*60
1280 TM$=MID$(T$,4,2):TMM=VAL(TM$)
1290 TC=TMM+THM
1300 '
1310 TR=TM-(TIMER-TC):GOSUB 2110:IF TR<=0.0001 GOTO 1390
1320 IF I$="M" THEN TR=(INT(100*(TR/60)))/100:LOCATE 10,15:
PRINT USING "TIME REMAINING BEFORE NEXT SAMPLE IN MINUTES
##.##";TR:GOTO 1340
1330 IF I$="H" THEN TRM=INT(((TR/3600)-
(INT(TR/3600)))*6000)/100:TR =(INT(TR/3600)):LOCATE
10,10:PRINT USING "TIME REMAINING BEFORE NEXT SAMPLE ## HOURS
AND ##.## MIN"'TR;TRM::GOTO 990
1340 LOCATE 12,27:PRINT USING "### SAMPLES HAVE BEEN TAKEN";N
1350 LOCATE 16,20:PRINT "NUMBER OF PARTICLES PER mL FROM LAST
SAMPLE"
1360 LOCATE 18,17:PRINT USING "####### < 5 MICRONS AND #######
> 5 MICRONS";AP1,AP2 :GOTO 1310
1370 '
1380 '
1390 '
1400 '
1410 '
1420 '
1430 '
1440 '
1450 '
1460 '
1470 '
1480 OPEN "I", #1,"DASCON1.ADR":INPUT#1,BASADR%:CLOSE #1
1490 CH%=1
1500 IF TN=>6 THEN TN=0
1510 TN=TN+1
1520 IF TN<1 OR TN>6 THEN CLS:LOCATE 10,20:PRINT "WE HAVE A
PROBLEM ":END
1530 IF TN=1 THEN DIO%(0)=1:GOSUB 2200
1540 IF TN=2 THEN DIO%(0)=2:GOSUB 2200
1550 IF TN=3 THEN DIO5(0)=4:GOSUB 2200
1560 IF TN=4 THEN DIO%(0)=8:GOSUB 2200
1570 IF TN=5 THEN DIO%(0)=16:GOSUB 2200
1580 IF TN=6 THEN DIO%(0)=32:GOSUB 2200
1590 '
1600 '
1610 '
1620 '
1630 '
1640 '
1650 '
1670 ' THE DATA REFERS TO THE ACCUMULATOR BINS TO ACCESS FOR
17 PARTICLE SIZES
```

```
1680 DATA 0,183,210,260,308,352,392,430,464,497,527,555,581,
606,629,651,671
1690 '
1700 '
1710 ' SUBROUTINE TO CONTROL BALL VALVES
1720 '
1730 DEF SEG=0
1740 SG=256*PEEK(&H511)+PEEK(&H510)
1750 DASCON1=0
1760 SG=(327681!/16)+SG
1770 DEF SEG=SG
1780 BLOAD "DASCON1.BIN",0
1790 FOR I=1 TO 15 STEP 2
1800 '
1810 PASS%=PASS%+1
1820 '------------- CALL ROUTINE FOR MODE 9 - DIGITAL I/O ----
--
1830 MD%=9
1840 CH%=1
1850 DIO%(1)=0
1860 FOR J=1 TO 100: NEXT J
1870 CALL DASCON1 (MD%,CH%,DIO%(0),DIO%(1),BASADR%)
1880 '
1990 '
2000 NEXT I
2040 IF TN=6 GOTO 1120
2050 GOTO 510
2060 DEF SEG=&H1F74
2070 '
2080 RETURN
2090 '
2100   CLS:LOCATE   10,25:PRINT   "DATA   ACQUISITION
COMPLETED":LOCATE   12,23:CLS:PRINT   "SAMPLING
FINISHED":CLOSE:END
2110 '----------------- COLLECT DATA FROM DATA LOGGER --------
--
2120 WHILE (NOT EOF(3)) AND LOC(3) >0
2130 A$=INPUT$(LOC(3),#3):PRINT A$;:PRINT #4,A$;
2140 ON ERROR GOTO 2130
2150 WEND
2160 RETURN
2170 '---------------------------------------------------------
--
2180 '
2190 ' SUBROUTINE FOR TIME DELAY
2200 '
2210 TDSTRT=TIMER:TDFIN=TDSTRT+20:TIMEUP=1
2220 WHILE TIMEUP
2230 TIMCURR = TIMER
2240 IF TIMCURR >= TDFIN THEN TIMEUP=0
2250 WEND
2260 RETURN
```

Appendix D: Calculation of Median, Mode and Mean Particle Size

Calculation of median:

The calculation of median, mode and mean particle size is performed using the average particle counts at the particle sizes for the swine housing dust as are provided in Table 6-1.

Nt = 40.55 particles/mL, 1/2Nt = 20.27

The median particle size, d_{NM} is that at which 50% of the total number of particles are less than and greater than d_{NM}. The cumulative number count of particles less than 1 μm to total particle count is 0.21. The particles required to increase the count ratio from 0.21 to 0.50 are within the particle size range of 1 to 2 μm.

$$0.50 - 0.21 = 0.29 \; ; \; 0.29 \times 40.55 = 11.8 \text{ particles/mL}$$

Assuming the total concentration of 16.4 particles/mL within the size range of 1 to 2 μm, is evenly distributed, the size at which the cumulative concentration within this size range is 11.8 particles/mL is as follows:

$$11.8 \text{ particles/mL} \cdot (16.4 \text{ particles/mL})^{-1} = 0.72$$

$$0.72 \cdot 1\ \mu m = 0.72\ \mu m$$

Therefore the median particle size is:

$$1\ \mu m + 0.72\ \mu m = 1.72\ \mu m.$$

Calculation of the mode:

The modal particle size is made by analysis of the particle size distribution curve. The mode is the particle size at which the particle number count is the highest among all particle sizes. The highest particle count was 16.4

particles/mL within the size range of 1 to 2 μm. The mode therefore is approximately at the avergae size, 1.5 μm, within the size range of 1 to 2 μm.

Calculation of the mean:

$$\begin{aligned} d_{mean} &= Nt^{-1} \cdot \Sigma(n_d \cdot d_p) \\ &= (40.55)^{-1} \cdot (\,0.25 \cdot 4.4 + 0.75 \cdot 4.2 + 1.5 \cdot 16.4 \\ &\qquad +2.5 \cdot 9.7 + 3.5 \cdot 3.8 + 4.5 \cdot 1.4 + \\ &\qquad 5.5 \cdot 0.44 + 6.5 \cdot 0.15 + 7.5 \cdot 0.14) \\ &= 1.9\ \mu m \end{aligned}$$

where: d_{mean} = mean particle size, μm,
Nt = total particle concentration, particles/mL,
n_d = particle concentration within size range d, particles/mL, and
d_p = average particle size, μm.

Appendix E: Sample Calculation of η_0

For voltage level 1, airspeed level 1 (Average of three replicates):

Particle Size Range (μm)	Particle concentration (particles/mL)	Collection Efficiency (%)
$d < 0.5$	5.5	28.9
$0.5 < d < 1$	4.1	29.9
$1 < d < 2$	16.7	36.5
$2 < d < 3$	10.9	42.4
$3 < d < 4$	3.1	45.3
$4 < d < 5$	0.96	48.0
$5 < d < 6$	0.31	51.8
$6 < d < 7$	0.12	52.0
$7 < d < 8$	0.05	50.0

$$\begin{aligned}\eta_0 &= Nt^{-1} \cdot \Sigma (\eta_d \cdot n_d) \\ &= (41.88)^{-1} \cdot (5.5 \cdot 28.9 + 4.1 \cdot 29.9 + 16.7 \cdot 36.5 + 10.9 \cdot 42.4 + 3.1 \cdot 45.3 + 0.96 \cdot 48 + 0.31 \cdot 51.8 + 0.12 \cdot 52 + 0.05 \cdot 50.0) \\ &= 37.5\ \%\end{aligned}$$

General Linear Models Procedure

Dependent Variable: EF (efficiency)

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Model	107	235023	2196.5	15.59	0.0001
Error	162	22820	140.9		
Corrected Total	269	257844			
	R-Square	C.V.	Root MSE		EF Mean
	0.91	21.29	11.87		55.75
Source	DF	Type I SS	Mean Square	F Value	Pr > F
V	2	201285	100642	714.4	0.0001
S	2	2406	1203	8.5	0.0003
V*S	4	3836	959	6.8	0.0001
R(V*S)	18	14229	791	5.6	0.0001
C	9	1540	171	1.2	0.2890
V*C	18	6099	339	2.4	0.0020
S*C	18	2363	131	0.9	0.5412
V*S*C	36	3263	91	0.6	0.9398

where, V - Applied voltage
S - Airspeed
R - Replicates
C - Samples

In the next section the variables, voltage (V) and airspeed (S) as well as their interaction (V*S) are tested against the suitable error term (R(V*S). This error term was determined to be the suitable from the EMS Table produced by SAS 6.0.

```
          Tests of Hypothesis for Mixed Model Analysis of
Variance

Dependent variable: Collection efficiency

      Source: V *
        Error: MS(R(V*S))

  DF    Type III MS  Denominator  Denominator  F Value    Pr>F
                          DF           MS
  2     100642.75          18        790.55     127.3  0.0001
       * This test assumes one or more other fixed effects are
zero.

        Source: S *
        Error: MS(R(V*S))

  DF    Type III MS  Denominator  Denominator  F Value    Pr>F
                          DF           MS
  2       1203.11          18        790.55       1.5  0.2451
       * This test assumes one or more other fixed effects are
zero.

        Source: V*S *
        Error: MS(R(V*S))

  DF   Type III MS  Denominator  Denominator  F Value    Pr>F
                         DF           MS
  4        959.06          18        790.55       1.2  0.3397
       * This test assumes one or more other fixed effects are
zero.
```

Since the test hypothesis was that the LSMEAN(i)=LSMEAN(j); any value of Pr>F exceeding 0.05 proves the hypothesis true. For the test on the significance of voltage on collection efficiency, Pr>F is 0.0001, implying that LSMEAN(i)≠LSMEAN(j), between different levels of votlage. Therefore voltage (V) has a significant effect on collection efficiency. Airspeed (S) does not have a significant effect upon collection efficiency. The interaction between voltage and airspeed (V*S) is not significant.

Appendix F: Sample Calculation of ϖ and ϖ_k

The sample calculations of the original and modified effective migration velocity were made using the following values:

v, airspeed = $0.55\ \mathrm{m \cdot s^{-1}}$,
L, precipitator length = 0.6096 m,
S, inter-electrode spacing = 0.01524 m,
η_0, collection efficiency = 37.8 %.

Using the original Deutsch-Anderson relationship:

$$\eta_0 = 100 \cdot [\ 1 - \exp\ (\ - \varpi \cdot L \cdot v^{-1} \cdot S^{-1})\ ],$$

$$\eta_0/100 = 1 - \exp\ (\ - \varpi \cdot L \cdot v^{-1} \cdot S^{-1}),$$

$$1 - \varpi_0/100 = \exp\ (\ - \varpi \cdot L \cdot v^{-1} \cdot S^{-1}),$$

$$\ln(\ 1 - \eta_0/100\ ) = - \varpi \cdot L \cdot v^{-1} \cdot S^{-1},$$

$$\varpi = - \ln(\ 1 - \eta_0/100) \cdot v \cdot S \cdot L^{-1},$$

$$\varpi = - \ln(\ 1 - 0.378) \cdot 0.55 \cdot 0.01524 \cdot 0.6096^{-1}$$
$$= 0.0065\ \mathrm{m/s}$$

Using the modified Deutsch-Anderson relationship:

$$\eta_0 = 100 \cdot [\ 1 - \exp\ (\ -(\varpi_k \cdot L \cdot v^{-1} \cdot S^{-1})^{0.5})\ ],$$

$$\eta_0/100 = [\ 1 - \exp\ (-(\varpi_k \cdot L \cdot v^{-1} \cdot S^{-1})^{0.5})\ ],$$

$$1 - \eta_0/100 = \exp(-(\varpi_k \cdot L \cdot v^{-1} \cdot S^{-1})^{0.5})\ ],$$

$$\ln(\ 1 - \eta_0/100) = - (\varpi_k \cdot L \cdot v^{-1} \cdot S^{-1})^{0.5},$$

$$[-\ln(\ 1 - \eta_0/100)\ ]^2 = \varpi_k \cdot L \cdot v^{-1} \cdot S^{-1},$$

$$\varpi_k = [-\ln(\ 1 - \eta_0/100)\ ]^2 \cdot v \cdot S \cdot L^{-1},$$

$$\varpi_k = [-\ln(\ 1 - 0.378)\ ]^2 \cdot 0.55 \cdot 0.01524 \cdot 0.6096^{-1}$$
$$= 0.0031\ \mathrm{m/s}$$

Appendix G: Sample Calculation of η_0 Varying Precipitator Lengths

The original precipitator length of the prototype is 0.6096 m. Using the modified Deutsch-Anderson Equation:

$$\eta_{0k} = 100 \cdot [\ 1 - \exp\ (\ -(\tilde{\omega}_k \cdot L \cdot v^{-1} \cdot S^{-1})^{0.5})\ ]$$

where η_{0k} = modified collection efficiency, %,
$\tilde{\omega}_k$ = modified effective migration velocity, $m \cdot s^{-1}$,
= 0.0031 m/s
L = Precipitator length, m,
= 0.9 m
v = airspeed, $m \cdot s^{-1}$,
= 0.55 m/s
S = inter-electrode spacing, m,
= 0.01524 m.

$$\eta_{0k} = 100 \cdot [\ 1 - \exp\ (-(0.0031 \cdot 0.9 \cdot 0.55^{-1} \cdot 0.015^{-1})^{0.5})\ ]$$

$$= 100 \cdot [\ 0.433\ ]$$

$$= 43.8\ \%$$

Appendix H: Sample Calculation of η_0 at Varying Inter-electrode Spacings

The original inter-electrode spacing of the prototype is 0.01524 m. Using the modified Deutsch-Anderson Equation:

$$\eta_{0k} = 100 \cdot [\ 1 - \exp\ (\ -(\tilde{\omega}_k \cdot L \cdot v^{-1} \cdot S^{-1})^{0.5})\ ]$$

where η_{0k} = modified collection efficiency, %,
$\tilde{\omega}_k$ = modified effective migration velocity, $m \cdot s^{-1}$,
= 0.0031 m/s
L = precipitator length, m,
= 0.6096 m
v = airspeed, $m \cdot s^{-1}$,
= 0.55 m/s, and
S = inter-electrode spacing, m,
= 0.009 m

$$\eta_{0k} = 100 \cdot [\ 1 - \exp\ (\ -(0.0031 \cdot 0.6096 \cdot 0.55^{-1} \cdot 0.009^{-1})^{0.5})]$$

$$= 100 \cdot [\ 0.461\ ]$$

$$= 46.1\ \%$$

APPENDIX I: Sample Calculation of Ozone Production

The measured O_3 concentration for an applied voltage of -12300 VDC and an airspeed level of 0.55 m/s was used in the sample calculation.

After a 1-h run the concentration was 0.25 ppm.
Correcting for the pressure change = 0.25 ppm · 1.08
C_{ozone} = 0.27 ppm

The exhaust fan operated at $Q_{exhaust} = 1072\ m^3/h$.

$$\text{Total } O_3 \text{ produced} = C_{ozone} \cdot Q_{exhaust} \cdot 10^6\ mL \cdot m^{-3} \cdot 10^{-6}$$
$$= 0.27\ ppm \cdot 1072\ m^3 \cdot h^{-1} \cdot 10^6\ mL \cdot m^{-3} \cdot 10^{-6}$$
$$= 289\ mL \cdot h^{-1}.$$

Ozone produced per wire length
$$= 289\ mL \cdot h^{-1} \cdot (15.6\ m)^{-1}$$
$$= 18.5\ mL \cdot h^{-1} \cdot m^{-1}$$

Ozone produced per current
$$= 289\ mL \cdot h^{-1} \cdot (2.95\ mA)^{-1}$$
$$= 98.0\ mL \cdot h^{-1} \cdot mA^{-1}.$$

APPENDIX J: Data Used to Calculate Collection Efficiency

Table J-1: Collection efficiency data for applied voltage of -10.3 kVDC

		*d< 0.5	d< 0.5	0.5< d<1	0.5< d<1	1 <d<2	1 <d<2	2 <d<3	2 <d<3	3 <d<4	3 <d<4	4 <d<5	4 <d<5	5 <d<6	5 <d<6	6 <d<7	6 <d<7	7 <d<8	7 <d<8		
		n_d[1]	η_d[2]	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	η_o	N_t
		#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	%	#/mL
Airspeed = 0.55 m/s																					
Rep	Sample																				
1	1	1	61	1	36	4	51	2	44	1	55	0	74	0	56	0	50	0	50	51	9
	2	2	43	2	37	11	39	6	39	2	40	1	44	0	54	0	60	0	61	40	25
	3	2	43	2	42	10	44	6	53	2	58	1	54	0	62	0	71	0	47	48	23
	4	2	44	2	27	10	44	7	51	2	54	1	56	0	48	0	69	0	62	46	24
	5	2	37	2	39	11	43	7	50	3	57	1	53	0	59	0	56	0	56	46	26
	6	2	28	2	41	12	41	8	51	3	47	1	59	0	60	0	67	0	11	45	27
	7	3	57	3	50	13	46	7	44	2	47	1	43	0	40	0	56	0	86	47	28
	8	2	42	2	37	10	35	6	36	2	41	1	47	0	49	0	48	0	63	37	24
	9	2	10	2	35	11	30	7	36	3	42	1	41	0	42	0	57	0	84	33	26
	10	2	27	2	19	12	32	8	39	3	42	1	44	0	56	0	35	0	40	35	27
	Avg	2	39	2	36	10	40	6	44	2	48	1	51	0	53	0	57	0	56	43	24
2	1	8	-6	5	-6	19	-2	15	4	4	1	1	10	0	41	0	50	0	-10	0	52
	2	10	46	6	46	24	52	17	55	4	54	1	50	0	57	0	81	0	45	51	63
	3	9	34	6	40	22	38	15	41	3	44	1	45	0	46	0	32	0	20	39	57
	4	10	38	7	39	24	45	17	47	4	50	1	46	0	45	0	48	0	36	44	64

	5	10	43	7	41	25	45	17	48	4	47	1	56	0	51	0	67	0	65	46	64
	6	10	38	7	40	26	43	18	43	4	42	1	50	0	54	0	60	0	18	42	66
	7	9	36	6	38	22	44	16	46	4	48	1	54	0	53	0	52	0	33	43	57
	8	12	52	8	55	29	56	21	59	5	60	1	64	0	64	0	82	0	17	56	77
	9	10	40	7	39	24	41	17	44	4	50	1	51	0	53	0	60	0	93	42	64
	10	11	41	7	41	26	40	18	41	4	46	1	38	0	40	0	60	0	44	41	67
	Avg	10	36	6	37	24	40	17	43	4	44	1	46	0	50	0	59	0	36	40	63
3	1	6	7	4	-1	10	15	6	36	3	49	1	54	0	54	0	48	0	61	21	30
	2	5	31	5	31	19	42	12	49	4	53	1	48	0	49	0	54	0	71	43	47
	3	5	-41	4	-3	17	30	10	44	4	48	1	57	0	57	0	41	0	62	24	42
	4	4	16	3	19	11	31	7	40	2	50	1	55	0	52	0	38	0	44	32	28
	5	5	32	4	32	15	42	9	52	3	56	1	45	0	67	0	73	0	75	44	37
	6	5	24	4	24	17	35	10	42	3	44	1	50	0	60	0	43	0	58	36	42
	7	5	23	4	21	16	31	10	43	3	39	1	47	0	50	0	35	0	30	33	40
	8	6	40	5	30	18	37	10	31	3	33	1	39	0	50	0	17	0	64	35	43
	9	4	23	4	25	17	30	11	41	4	45	1	54	0	55	0	41	0	54	34	42
	10	3	-42	3	-14	14	-5	9	25	3	19	1	13	0	28	0	10	0	59	2	34
	Avg	5	11	4	16	15	29	9	40	3	43	1	46	0	52	0	40	0	58	30	39
	Avg	5	29	4	30	17	36	11	42	3	45	1	48	0	52	0	52	0	50	38	42

Airspeed = 0.76 m/s																					
1	1	6	17	5	24	20	25	14	28	4	28	1	35	0	47	0	60	0	80	25	51
	2	10	28	9	37	29	31	20	34	5	37	1	47	0	31	0	32	0	64	33	76
	3	9	42	8	42	26	44	18	45	5	48	1	46	0	47	0	52	0	30	44	67
	4	9	37	7	39	25	40	17	44	4	43	1	50	0	17	0	60	0	57	41	65
	5	10	38	7	34	28	41	19	42	5	46	1	44	0	51	0	42	0	65	41	71
	6	21	13	16	7	60	22	39	24	10	29	3	37	1	31	0	25	0	48	20	150
	7	10	50	8	47	29	51	20	52	5	54	1	57	0	59	0	59	0	72	51	74
	8	9	45	7	42	26	47	17	45	4	43	1	52	0	60	0	25	0	38	46	64
	9	7	23	5	21	20	25	14	27	4	28	1	26	0	53	0	46	0	33	25	51
	10	6	15	5	14	18	20	12	23	3	25	1	23	0	47	0	0	0	9	20	45
	Avg	10	31	8	31	28	35	19	37	5	38	1	42	0	44	0	40	0	50	35	71
2	1	2	-26	3	-19	12	-7	8	4	3	15	1	19	0	18	0	30	0	48	-3	31
	2	3	0	5	12	15	12	8	7	2	16	1	16	0	-9	0	0	0	-88	10	33
	3	4	-14	5	-10	17	-11	8	-14	2	-18	1	-37	0	-35	0	-57	0	-17	-13	37
	4	7	12	11	12	32	9	14	7	4	7	1	-8	0	-18	0	37	0	-50	9	68
	5	4	-14	7	-8	20	-13	9	-20	2	-25	1	-37	0	-16	0	-48	0	31	-15	43
	6	5	8	8	10	24	12	10	11	2	7	1	11	0	-9	0	4	0	-9	11	50
	7	4	25	6	26	20	28	8	23	2	16	1	23	0	19	0	18	0	64	26	41
	8	5	23	7	19	20	19	8	16	2	6	1	17	0	6	0	47	0	-38	18	43
	9	5	11	7	6	21	8	9	6	2	3	1	-2	0	0	0	-8	0	22	7	45

	10	4	22	6	23	17	20	7	19	2	22	1	9	0	11	0	33	0	0	20	37
	Avg	4	5	6	7	20	8	9	6	2	5	1	1	0	-3	0	6	0	-4	7	43
3	1	0	42	0	27	1	31	0	41	0	52	0	75	0	61	0	0	0	100	45	2
	2	1	34	1	27	14	36	9	42	6	48	3	51	1	41	0	64	0	62	41	35
	3	1	11	2	32	16	41	9	52	5	56	2	62	1	64	0	56	0	58	47	36
	4	1	26	1	18	15	34	8	42	5	46	2	51	1	55	0	66	0	43	39	33
	5	1	43	2	41	17	40	9	48	6	52	2	51	1	56	0	55	0	58	45	37
	6	1	45	1	39	12	40	6	53	4	47	1	52	0	55	0	26	0	7	45	27
	7	1	29	1	19	13	24	7	37	5	40	2	48	1	38	0	54	0	71	32	31
	8	1	29	1	20	14	34	8	42	5	44	2	50	1	58	0	54	0	50	39	33
	9	1	23	2	24	17	29	9	43	6	45	2	49	1	58	0	41	0	52	37	38
	10	0	51	1	36	5	42	3	50	1	50	0	52	0	60	0	50	0	0	46	10
	Avg	1	33	1	28	12	35	7	45	4	48	2	54	1	55	0	46	0	50	41	28
	Avg	5	23	5	22	20	26	12	29	4	30	1	32	0	32	0	31	0	32	28	47
Airspeed = 0.95 m/s																					
1	1	1	-70	2	-58	5	-57	3	-44	1	-41	0	-69	0	-39	0	-67	0	17	-54	12
	2	3	-11	4	-8	14	-3	6	-6	1	-20	0	-20	0	-27	0	-25	0	-80	-7	29
	3	3	-4	4	-2	13	-1	6	1	1	-15	0	-34	0	-3	0	-67	0	0	-2	28
	4	3	30	4	32	13	33	6	31	1	21	0	26	0	-3	0	0	0	90	31	28

	5	3	24	4	26	13	28	5	29	1	28	0	17	0	-55	0	0	0	60	27	26
	6	2	14	4	19	13	24	5	24	1	24	0	-4	0	53	0	56	0	50	22	26
	7	3	35	5	34	15	37	6	39	2	35	0	50	0	44	0	36	0	100	37	31
	8	3	23	4	27	13	31	5	33	1	36	0	7	0	-5	0	45	0	100	30	27
	9	3	18	4	21	12	22	5	20	1	23	0	35	0	14	0	0	0	50	21	26
	10	3	21	4	24	12	27	5	30	1	25	0	33	0	4	0	43	0	50	27	26
	Avg	3	8	4	11	12	14	5	16	1	11	0	4	0	-2	0	2	0	44	13	26
2	1	7	-29	5	-23	15	-23	8	-25	2	-18	1	-31	0	2	0	8	0	-42	-24	39
	2	14	12	10	4	27	8	14	7	3	3	1	-21	0	-41	0	-14	0	-10	8	69
	3	18	-9	13	-10	35	-10	16	-12	3	-18	1	-25	0	-34	0	7	0	-60	-10	87
	4	11	3	7	0	22	5	11	-1	2	-5	1	-6	0	0	0	4	0	57	2	53
	5	11	29	8	24	27	29	16	26	4	20	1	-6	0	28	0	57	0	25	27	67
	6	10	21	9	26	30	28	19	25	5	29	1	27	0	25	0	27	0	13	26	74
	7	11	37	9	33	32	40	20	39	5	35	1	43	0	43	0	26	0	36	38	78
	8	11	5	9	8	30	16	18	19	4	16	1	3	0	43	0	27	0	39	14	74
	9	10	7	8	6	29	7	19	10	5	7	1	1	0	15	0	-27	0	-89	7	73
	10	8	20	7	22	27	25	18	29	5	31	1	25	0	26	0	46	0	31	26	66
	Avg	11	10	8	9	27	13	16	12	4	10	1	1	0	11	0	16	0	0	11	68
3	1	9	21	5	23	20	26	15	32	3	28	1	28	0	47	0	36	0	53	27	52
	2	10	23	7	29	24	29	17	29	4	28	1	32	0	9	0	0	0	38	28	63
	3	12	46	7	42	27	47	19	49	4	51	1	41	0	57	0	44	0	56	47	70

	4	12	36	7	37	28	40	20	42	4	41	1	39	0	30	0	56	0	57	40	73
	5	11	34	7	34	27	40	19	42	4	40	1	43	0	30	0	45	0	92	39	71
	6	13	38	8	37	29	39	20	40	4	42	1	42	0	49	0	54	0	67	39	76
	7	12	12	8	14	27	14	19	18	4	24	1	17	0	31	0	-4	0	25	15	71
	8	9	19	5	26	19	24	12	24	3	34	1	27	0	26	0	16	0	33	24	49
	9	9	33	5	30	15	31	8	29	2	31	0	36	0	26	0	47	0	77	31	40
	10	11	21	6	20	19	24	10	21	2	22	1	33	0	40	0	71	0	0	22	50
	Avg	11	28	7	29	23	31	16	33	3	34	1	34	0	34	0	37	0	50	31	61
	Avg	8	15	6	16	21	19	12	20	3	19	1	13	0	15	0	18	0	31	19	52

* d - particle size (μm)

[1] n_d - particle concentration for size range d, (particles/mL)

[2] η_d - collection efficiency for size range d, (particles/mL)

Table J-2: Collection efficiency data for applied voltage of -11.0 kVDC

		d< 0.5	d< 0.5	0.5< d<1	0.5< d<1	1 <d<2	1 <d<2	2 <d<3	2 <d<3	3 <d<4	3 <d<4	4 <d<5	4 <d<5	5 <d<6	5 <d<6	6 <d<7	6 <d<7	7 <d<8	7 <d<8		
		n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	η_o	N_t
		#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	%	#/mL
Airspeed = 0.55 m/s																					
Rep	Sample																				
1	1	1	58	3	66	10	62	7	69	2	68	1	69	0	54	0	70	0	100	65	23
	2	3	83	4	82	17	87	10	92	3	93	1	91	0	97	0	100	0	100	88	39
	3	3	63	5	66	18	71	10	78	3	80	1	83	0	85	0	91	0	100	72	40
	4	5	-66	6	-14	19	29	10	63	3	65	1	56	0	72	0	56	0	88	22	44
	5	10	-86	9	-75	22	-7	9	72	2	73	1	76	0	78	0	72	0	75	-16	54
	6	5	-99	6	-13	18	41	10	81	3	85	1	87	0	87	0	88	0	78	31	43
	7	15	11	13	23	29	46	10	73	3	77	1	70	0	78	0	55	0	56	40	71
	8	7	4	7	33	19	48	9	66	3	71	1	65	0	76	0	75	0	100	45	45
	9	12	25	10	31	24	45	9	55	2	58	1	62	0	62	0	52	0	100	41	58
	10	10	17	8	31	20	40	8	56	2	55	1	46	0	58	0	47	0	-50	38	49
	Avg	7	1	7	23	20	46	9	71	2	73	1	71	0	75	0	71	0	75	43	46
2	1	2	-5	1	9	5	18	3	34	1	41	1	47	0	66	0	56	0	72	22	14
	2	8	56	5	59	18	69	10	75	4	78	1	73	1	80	0	84	0	67	68	47
	3	8	39	5	38	18	54	10	59	4	56	2	65	1	63	0	67	0	76	51	49
	4	10	57	7	56	21	56	12	64	5	63	2	67	1	76	0	57	0	67	59	57
	5	9	42	6	44	19	60	11	65	5	66	2	67	1	72	0	80	0	75	57	52

	6	19	59	12	57	27	68	13	71	6	77	2	75	1	77	0	81	0	83	66	80
	7	8	34	6	38	13	59	5	55	2	60	1	57	0	67	0	46	0	53	49	35
	8	11	30	7	27	17	59	9	65	4	71	1	71	0	67	0	69	0	79	51	50
	9	13	45	9	50	19	61	8	61	4	63	1	68	0	81	0	68	0	73	56	54
	10	9	5	5	-1	14	20	8	26	3	26	1	25	0	14	0	41	0	36	16	41
	Avg	10	36	6	38	17	52	9	57	4	60	1	61	0	66	0	65	0	68	49	48
3	1	2	40	2	45	7	47	7	59	3	68	1	76	0	79	0	83	0	57	54	22
	2	2	45	2	40	8	49	6	53	1	55	0	55	0	63	0	50	0	67	50	19
	3	3	17	2	13	9	27	7	38	2	39	1	47	0	62	0	38	0	89	30	24
	4	5	50	4	54	16	60	11	71	3	76	1	79	0	85	0	63	0	100	63	40
	5	3	42	2	40	9	47	7	54	2	47	0	58	0	55	0	64	0	0	48	23
	6	6	38	5	40	20	42	15	50	4	52	1	59	0	68	0	79	0	75	45	51
	7	7	39	6	39	24	45	18	48	4	49	1	44	0	65	0	84	0	81	45	61
	8	6	22	5	25	21	30	15	32	3	35	1	40	0	51	0	30	0	67	30	52
	9	6	28	5	31	20	34	15	39	4	43	1	38	0	53	0	46	0	33	35	52
	10	2	-3	1	8	5	17	3	35	1	41	1	47	0	66	0	56	0	72	22	14
	Avg	4	36	4	36	15	42	11	49	3	51	1	55	0	64	0	60	0	63	44	38
	Avg	7	24	6	32	17	47	10	59	3	61	1	62	0	68	0	65	0	69	45	44

Airspeed = 0.76 m/s

1	1	1	-2	2	3	7	11	4	29	2	45	1	50	0	60	0	75	0	69	20	16
	2	3	29	5	33	20	44	12	54	3	56	1	65	0	70	0	70	0	56	46	44
	3	3	20	6	27	22	37	14	46	4	47	1	47	0	52	0	43	0	17	38	50
	4	4	10	6	11	25	26	15	35	4	38	1	34	0	58	0	65	0	9	27	56
	5	5	49	8	39	30	44	17	46	4	47	1	50	0	54	0	33	0	80	44	66
	6	4	25	8	25	33	33	21	38	5	39	1	34	0	37	0	34	0	9	33	72
	7	5	26	8	24	32	30	18	30	5	26	1	35	0	57	0	42	0	63	29	70
	8	4	32	7	32	28	37	17	40	4	38	1	38	0	49	0	58	0	87	37	62
	9	4	39	8	40	31	41	18	43	5	47	1	39	0	59	0	43	0	56	42	68
	10	4	20	6	24	24	26	14	23	3	29	1	27	0	34	0	37	0	40	25	52
	Avg	4	25	6	26	25	33	15	38	4	41	1	42	0	53	0	50	0	49	34	56
2	1	2	57	2	53	9	65	6	77	4	80	2	83	1	90	0	78	0	81	71	26
	2	2	48	2	49	10	56	7	71	4	74	2	74	1	84	0	83	0	71	63	29
	3	2	37	2	39	11	52	7	61	4	65	2	70	1	75	0	73	0	87	56	28
	4	2	38	3	34	11	38	8	54	4	55	2	57	1	56	0	69	0	66	46	30
	5	2	26	3	26	11	29	8	47	4	48	2	54	1	42	0	37	0	61	37	31
	6	2	31	2	33	9	32	6	48	3	41	2	51	1	53	0	43	0	62	39	24
	7	2	33	3	31	11	38	7	47	4	52	2	52	1	44	0	38	0	69	42	30
	8	2	14	2	15	10	16	7	24	4	26	2	23	1	26	0	16	0	7	20	28
	9	5	49	8	39	30	44	17	46	4	47	1	50	0	54	0	33	0	80	44	66
	10	0	52	1	30	15	44	10	55	8	55	3	59	1	62	0	64	0	61	51	39
	Avg	2	35	2	35	10	41	7	53	4	55	2	58	1	59	0	54	0	63	47	28

3	1	0	64	0	62	5	62	3	68	3	69	1	72	0	69	0	56	0	43	66	14
	2	0	62	1	48	11	55	7	66	6	65	3	68	1	76	0	82	0	77	62	28
	3	0	63	1	56	17	53	11	67	9	66	4	70	1	70	0	66	0	86	62	43
	4	1	59	1	49	24	53	15	63	13	65	5	69	1	75	0	65	0	77	60	61
	5	0	53	1	35	18	44	12	53	10	57	4	59	1	63	0	66	0	60	51	46
	6	0	40	1	39	16	48	10	60	9	63	4	65	1	66	0	64	0	69	56	41
	7	0	64	1	61	14	51	9	65	8	66	3	71	1	75	0	78	0	79	61	37
	8	0	47	1	47	15	48	10	59	9	63	4	67	1	63	0	72	0	71	56	41
	9	0	67	1	51	18	57	12	68	10	69	4	74	1	75	0	89	0	72	64	46
	10	0	53	1	29	15	45	10	55	8	55	3	59	1	62	0	64	0	61	51	39
	Avg	0	57	1	48	15	52	10	62	8	64	3	67	1	69	0	70	0	69	59	40
	Avg	2	39	3	36	17	42	11	51	5	53	2	56	1	60	0	58	0	60	47	41
Airspeed = 0.95 m/s																					
1	1	4	33	4	29	13	41	7	52	2	57	1	61	0	71	0	87	0	80	43	33
	2	4	23	5	30	16	32	10	55	3	54	1	63	0	48	0	47	0	20	39	38
	3	4	49	5	49	18	55	12	58	3	59	1	59	0	48	0	35	0	73	55	44
	4	4	31	6	39	22	45	16	50	5	56	1	54	0	47	0	70	0	82	46	55
	5	5	47	6	51	25	54	17	60	5	61	1	63	0	69	0	73	0	68	56	60
	6	5	56	5	57	21	61	15	63	4	66	1	63	0	66	0	66	0	64	61	51
	7	4	35	5	35	21	44	15	50	4	49	2	60	0	46	0	49	0	73	45	52

	8	5	28	6	34	23	37	17	45	5	46	1	45	0	57	0	53	0	53	39	59
	9	4	5	5	7	20	21	15	28	4	28	1	36	0	40	0	55	0	56	22	50
	10	4	34	5	41	20	44	15	50	5	54	1	53	0	65	0	61	0	33	46	52
	Avg	4	34	5	37	20	43	14	51	4	53	1	56	0	56	0	59	0	60	45	49
2	1	1	33	1	34	5	36	3	43	2	50	1	43	1	56	0	45	0	60	41	14
	2	1	25	2	33	7	38	5	48	3	47	1	41	0	39	0	26	0	0	40	20
	3	2	52	3	47	11	52	7	63	4	64	2	59	1	69	0	62	0	58	57	30
	4	3	47	4	38	15	45	8	35	5	35	2	38	1	32	0	34	0	28	40	38
	5	3	45	3	38	14	46	9	47	5	50	2	47	1	56	0	51	0	60	46	38
	6	2	29	3	29	12	30	8	40	5	38	2	42	1	45	0	41	0	55	34	33
	7	2	45	2	35	10	49	6	59	4	64	2	69	1	68	0	70	0	67	54	27
	8	4	56	4	38	14	42	7	35	5	34	2	41	1	37	0	17	0	60	41	36
	9	2	13	3	27	11	34	7	48	5	54	2	58	1	59	0	68	0	66	41	32
	10	2	29	3	30	11	33	8	50	5	52	2	53	1	64	0	60	0	49	42	32
	Avg	2	37	3	35	11	40	7	47	4	49	2	49	1	52	0	47	0	50	44	30
3	1	3	80	1	82	4	82	1	60	1	61	0	60	0	64	0	87	0	71	77	11
	2	1	43	1	48	4	54	3	69	2	70	1	74	0	66	0	63	0	65	61	11
	3	2	56	2	43	6	38	4	60	3	57	1	63	0	68	0	66	0	78	51	18
	4	2	63	2	60	8	61	4	57	3	62	1	62	1	72	0	66	0	78	61	22
	5	1	32	1	33	5	30	4	48	2	52	1	49	0	53	0	35	0	42	40	15
	6	1	67	1	54	5	50	3	43	2	50	1	39	0	51	0	36	0	50	51	13

	7	1	16	1	11	5	26	3	37	2	37	1	47	0	54	0	43	0	37	31	13
	8	3	72	3	60	10	61	7	63	5	65	3	75	1	75	1	80	0	77	65	32
	9	2	51	2	50	8	53	6	63	5	67	3	70	1	73	1	79	0	84	61	27
	10	2	55	2	43	6	39	4	33	2	40	1	42	0	46	0	42	0	48	40	17
	Avg	2	53	2	48	6	49	4	53	3	56	1	58	1	62	0	60	0	63	54	18
	Avg	3	42	3	40	12	44	8	50	4	53	1	54	1	57	0	55	0	58	48	32

Table J-3: Collection efficiency data for applied voltage of -12.1 kVDC

		d< 0.5	d< 0.5	0.5< d<1	0.5< d<1	1 <d<2	1 <d<2	2 <d<3	2 <d<3	3 <d<4	3 <d<4	4 <d<5	4 <d<5	5 <d<6	5 <d<6	6 <d<7	6 <d<7	7 <d<8	7 <d<8		
		n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	n_d	η_d	η_o	N_t
		#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	#/mL	%	%	#/mL
Airspeed = 0.55 m/s																					
1	1	7	98	7	98	27	98	21	99	7	99	2	99	1	100	0	100	0	100	98	72
	2	4	95	4	96	17	97	13	99	4	99	1	100	0	96	0	100	0	100	98	43
	3	4	91	4	95	17	96	13	98	4	99	1	100	0	97	0	100	0	100	96	44
	4	4	96	4	97	17	98	12	98	4	99	1	100	0	100	0	100	0	100	98	42
	5	3	94	3	94	11	96	8	97	2	98	1	99	0	98	0	100	0	100	96	28
	6	6	93	5	94	21	96	15	98	4	98	1	99	0	97	0	100	0	93	96	53
	7	5	92	5	94	18	96	13	97	4	98	1	99	0	99	0	96	0	88	96	46
	8	5	92	4	95	16	96	12	97	3	97	1	98	0	100	0	97	0	100	96	42
	9	5	92	4	93	16	95	12	97	3	98	1	98	0	100	0	96	0	100	95	41
	10	4	91	4	92	13	94	10	97	3	98	1	99	0	100	0	96	0	100	95	35
	Avg	5	93	4	95	17	96	13	98	4	98	1	99	0	99	0	99	0	98	96	44
2	1	1	94	1	97	5	98	2	99	1	99	0	100	0	100	0	100	0	100	98	11
	2	2	97	4	97	12	98	5	99	1	100	0	100	0	100	0	100	0	100	98	25
	3	3	94	5	95	14	97	6	99	2	100	0	100	0	100	0	100	0	100	97	30
	4	5	92	7	94	19	96	8	98	2	99	1	100	0	100	0	100	0	100	96	41
	5	6	93	8	91	24	95	10	98	2	99	1	100	0	100	0	100	0	100	95	51

	6	6	87	8	92	23	95	9	98	2	99	1	99	0	100	0	100	0	100	95	48
	7	4	84	6	86	18	91	8	94	2	96	0	99	0	98	0	95	0	100	90	38
	8	4	89	6	92	18	94	7	97	2	99	0	99	0	98	0	100	0	100	94	39
	9	8	91	10	92	31	94	16	97	4	99	1	99	0	99	0	97	0	100	95	71
	10	4	82	5	83	15	88	7	94	1	96	0	97	0	100	0	100	0	100	88	34
	Avg	4	90	6	92	18	95	8	97	2	99	1	99	0	99	0	99	0	100	95	39
3	1	0	98	0	99	7	99	8	100	11	100	6	100	2	100	1	100	0	100	100	36
	2	0	99	0	93	11	98	9	99	9	99	4	100	2	100	0	100	0	100	99	36
	3	0	98	0	95	11	97	9	99	8	100	4	100	1	100	0	100	0	100	99	34
	4	0	96	1	92	16	95	11	99	10	100	4	99	1	100	0	99	0	100	98	45
	5	0	95	1	95	19	96	13	99	12	99	5	100	2	100	0	100	0	100	98	53
	6	0	96	1	95	17	96	12	99	11	99	5	100	1	100	0	100	0	100	98	48
	7	0	98	1	97	16	97	12	99	11	99	5	100	2	100	1	100	0	100	98	47
	8	0	95	1	95	14	96	10	99	8	99	4	100	1	100	0	99	0	100	98	38
	9	0	95	1	92	13	95	9	99	8	99	4	99	1	100	0	100	0	100	98	36
	10	0	100	1	96	14	97	9	99	9	99	4	100	1	100	0	100	0	98	98	39
	Avg	0	97	1	95	14	97	10	99	10	99	5	100	1	100	0	100	0	100	98	41
	Avg	3	94	4	94	16	96	10	98	5	99	2	99	1	99	0	99	0	99	96	42
Airspeed = 0.76 m/s																					
1	1	0	97	0	90	4	96	3	99	2	99	1	99	0	99	0	98	0	100	98	11

	2	0	85	1	84	12	93	7	98	5	99	2	99	1	100	0	100	0	95	96	28
	3	0	82	1	83	11	91	6	97	4	98	2	98	1	98	0	100	0	100	94	25
	4	0	87	1	75	10	87	6	96	4	98	2	99	0	99	0	99	0	100	92	23
	5	0	89	1	80	13	86	7	94	5	96	2	98	1	99	0	100	0	100	91	30
	6	0	90	1	83	8	91	4	96	3	98	1	100	0	99	0	100	0	100	94	18
	7	0	84	1	83	11	89	6	96	5	98	2	98	1	98	0	94	0	93	93	26
	8	0	83	1	82	13	88	7	95	6	97	2	97	1	97	0	100	0	100	92	31
	9	1	90	1	79	15	86	8	93	6	96	2	97	1	99	0	98	0	100	91	34
	10	1	84	1	77	16	84	9	93	6	95	2	98	1	96	0	98	0	97	89	37
	Avg	0	87	1	82	11	89	6	96	5	98	2	98	1	98	0	99	0	98	93	26
2	1	6	89	7	91	22	93	9	97	2	99	1	99	0	99	0	100	0	100	93	47
	2	10	87	12	88	33	91	14	96	3	98	1	98	0	99	0	98	0	93	91	73
	3	5	87	6	87	17	92	7	96	2	96	0	95	0	98	0	100	0	100	91	37
	4	9	88	10	89	29	92	11	96	3	97	1	98	0	99	0	100	0	100	92	62
	5	7	83	8	85	22	89	9	94	2	98	1	97	0	100	0	94	0	100	89	48
	6	7	86	8	86	23	90	10	95	2	95	1	95	0	98	0	100	0	100	90	51
	7	7	88	8	88	23	91	10	96	2	98	1	99	0	100	0	100	0	100	92	52
	8	6	87	7	87	19	92	9	95	2	97	1	99	0	98	0	100	0	100	91	43
	9	6	87	7	90	21	92	9	95	2	98	1	99	0	100	0	100	0	100	92	47
	10	6	82	7	84	19	88	8	94	2	96	1	97	0	96	0	100	0	100	88	42
	Avg	7	86	8	87	23	91	10	95	2	97	1	98	0	99	0	99	0	99	91	51

3	1	7	61	5	70	17	91	10	99	4	100	2	100	1	99	0	99	0	96	87	45
	2	10	91	7	93	21	97	11	99	5	99	2	99	1	100	0	98	0	98	96	56
	3	5	77	3	83	9	86	5	100	2	100	1	100	0	99	0	97	0	100	88	25
	4	7	57	5	74	15	94	9	100	4	100	1	100	1	100	0	100	0	97	87	43
	5	13	82	8	86	21	96	9	100	4	100	2	99	1	99	0	100	0	100	93	58
	6	9	55	6	64	18	90	10	100	5	100	2	99	1	100	0	99	0	100	83	51
	7	10	69	6	75	16	92	8	99	4	99	1	99	0	99	0	97	0	100	87	46
	8	10	79	7	82	20	96	9	99	4	99	2	99	1	99	0	100	0	97	92	52
	9	11	70	7	77	19	92	9	99	4	100	2	99	1	99	0	100	0	97	88	52
	10	10	84	7	87	20	96	10	99	5	99	2	99	1	100	0	100	0	100	93	55
	Avg	9	73	6	79	18	93	9	99	4	99	2	99	1	99	0	99	0	99	89	48
	Avg	6	82	5	83	17	91	8	97	4	98	1	98	0	99	0	99	0	99	91	42
Airspeed = 0.95 m/s																					
1	1	0	98	0	98	8	99	5	100	4	100	2	100	1	100	0	99	0	100	99	22
	2	0	98	0	92	9	96	5	99	4	100	2	100	1	100	0	100	0	100	98	21
	3	0	94	0	93	10	95	6	98	5	99	2	100	1	100	0	100	0	100	97	24
	4	0	94	0	86	8	90	5	97	4	99	2	100	1	99	0	100	0	100	95	20
	5	0	92	0	83	9	87	5	95	4	98	2	99	1	98	0	100	0	100	93	22
	6	0	92	1	76	11	85	7	93	6	97	3	98	1	99	0	100	0	100	91	28
	7	0	92	0	82	11	87	6	95	5	97	2	99	1	99	0	100	0	100	92	27
	8	0	94	0	74	5	89	2	93	2	97	1	99	0	99	0	97	0	93	92	10
	9	0	92	0	84	10	86	7	95	6	97	3	99	1	99	0	99	0	96	92	28

	10	0	88	1	79	12	88	7	95	6	98	3	99	1	99	0	99	0	97	93	30
	Avg	0	93	0	85	9	90	6	96	5	98	2	99	1	99	0	99	0	99	94	23
2	1	1	82	2	87	7	89	3	96	1	98	0	99	0	96	0	100	0	100	91	15
	2	1	76	2	79	8	85	4	95	1	97	0	94	0	100	0	100	0	50	87	16
	3	1	73	2	74	9	79	4	91	1	92	0	97	0	98	0	100	0	89	82	18
	4	1	83	3	84	12	87	6	95	2	97	0	97	0	98	0	100	0	100	89	25
	5	1	87	3	87	11	91	5	97	2	98	0	98	0	97	0	100	0	100	92	22
	6	1	79	3	82	11	88	5	94	2	97	1	99	0	98	0	96	0	100	89	23
	7	1	71	3	76	12	81	5	90	2	94	1	96	0	96	0	100	0	100	83	24
	8	1	77	3	77	13	84	6	90	2	94	1	96	0	98	0	100	0	88	85	27
	9	2	83	3	82	13	87	6	95	2	98	1	99	0	100	0	100	0	100	89	27
	10	1	77	3	83	12	87	6	95	2	97	0	99	0	97	0	100	0	100	89	25
	Avg	1	79	3	81	11	86	5	94	2	96	0	97	0	98	0	100	0	93	88	22
3	1	0	92	0	90	1	98	1	100	1	100	0	100	0	100	0	100	0	100	99	4
	2	0	92	0	97	4	96	2	98	2	99	1	100	0	99	0	97	0	100	98	10
	3	0	93	1	88	8	89	6	96	6	98	4	99	1	100	1	100	0	100	95	27
	4	0	74	1	74	10	84	6	93	5	97	2	99	1	99	0	99	0	100	90	25
	5	0	80	1	75	10	82	6	93	5	95	2	96	1	97	0	96	0	100	89	25
	6	0	73	1	72	11	83	6	92	5	95	2	98	1	98	0	100	0	100	89	26
	7	0	72	1	76	10	83	6	90	5	95	2	97	1	99	0	99	0	100	88	24
	8	0	82	1	70	11	81	6	92	5	96	2	98	1	99	0	98	0	96	88	27

	9	0	91	1	76	11	83	7	92	5	95	2	97	1	99	0	100	0	100	89	28
	10	0	79	1	76	12	81	7	91	5	93	2	96	1	98	0	96	0	96	87	28
	Avg	0	83	1	79	9	86	5	94	4	96	2	98	1	99	0	98	0	99	91	22
	Avg	1	85	1	82	10	87	5	94	4	97	2	98	1	99	0	99	0	97	91	23

Note - values of $n_d = 0$ represent dust concentrations between 0 and 1 particles/mL.